ERO predictive modelling for ITER component lifetime and benchmarking experiments for Be erosion at JET

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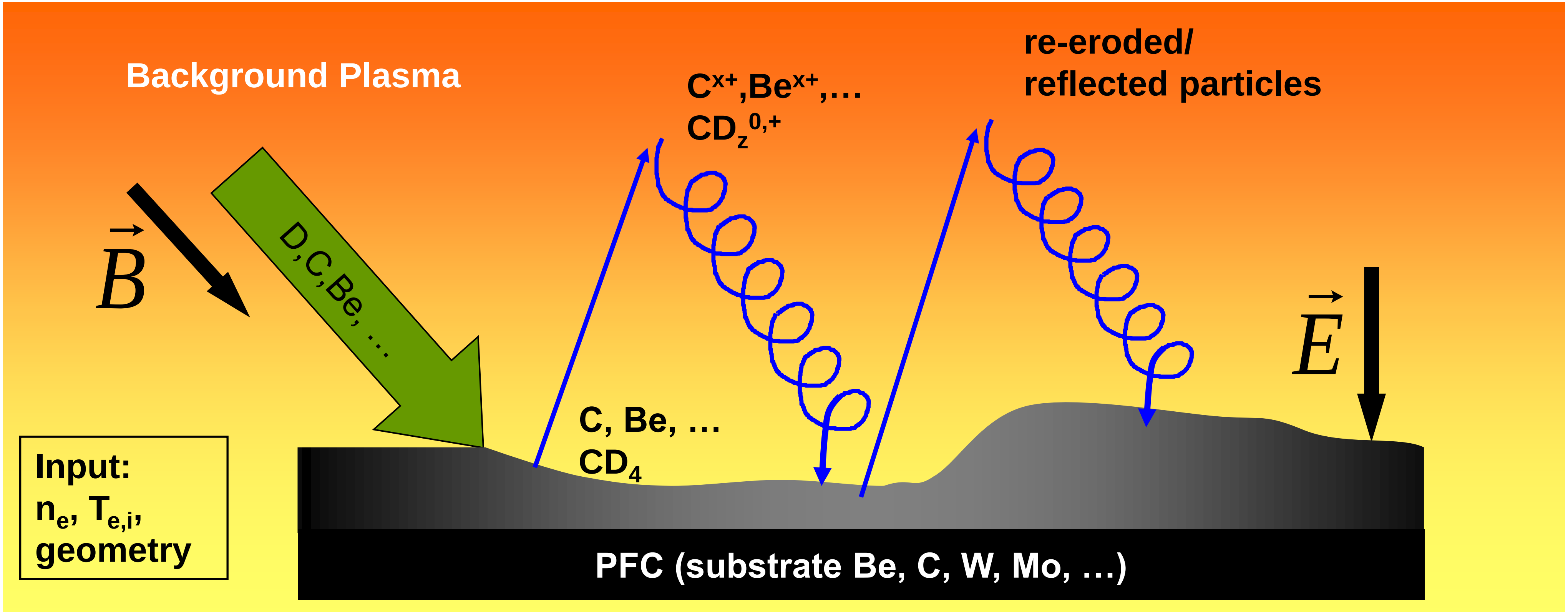
Zvenigorod conference on Plasma Physics and Controlled Fusion, 2013

Outline

- **ERO code introduction**
- ITER life time simulations
  - *General geometry, shadowing, plasma parameter . . .*
  - *Influence of intrinsic Be impurity*
  - *Net erosion - life time*
- Physical sputtering (data and uncertainties)
- Model benchmark at JET ILW
- Introduction of new physical effects into ERO
  - *Metastable states tracking*
  - *Be-D release and decay in plasma*
- Summary and outlook
- Further relevant experiments
  - *^{10}Be marker migration*
  - *ICRH Be antena erosion*

3D MC impurity transport code ERO



Local transport:

- ✓ ionisation, dissociation
- ✓ friction (Fokker-Planck), thermal force
- ✓ Lorenz force (including ExB component)
- ✓ cross-field diffusion

Plasma-surface interaction:

- ✓ physical sputtering/reflection
- ✓ chemical erosion (CD_4)
- ✓ (re-)erosion and (re-)deposition
- ✓ HMM and SDTrimSP surface models

ERO modelling strategy

Code development:
- *PSI & transport*
- *material mixing*
- *castellated surfaces*
- *atomic data, ADAS*

Benchmarking:
- ***JET ILW***
- *Pilot-PSI,* ***PSI-2, JULE-PSI***
- *TEXTOR, AUG,*
- *…*

Estimations for ITER:
- *tritium retention*
- *target & limiter lifetime*
- *impurities into plasma*

Coupling with other codes:
- *plasma parameters from: e.g. B2-Eirene, Edge-2D*
- *surface mixing: TriDyn, MolDyn*

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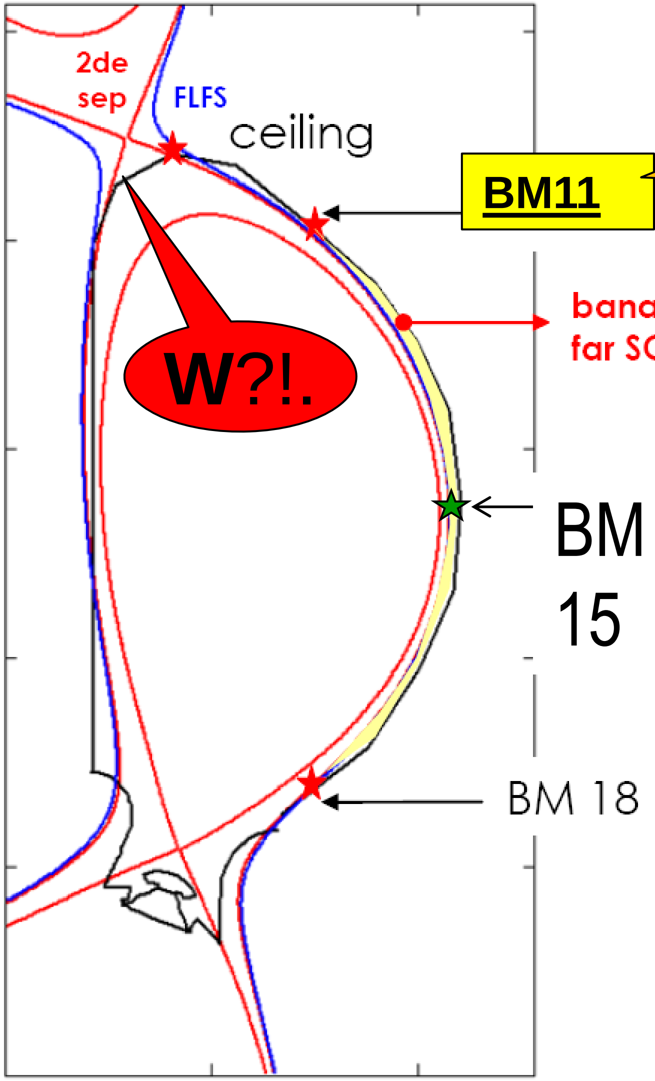
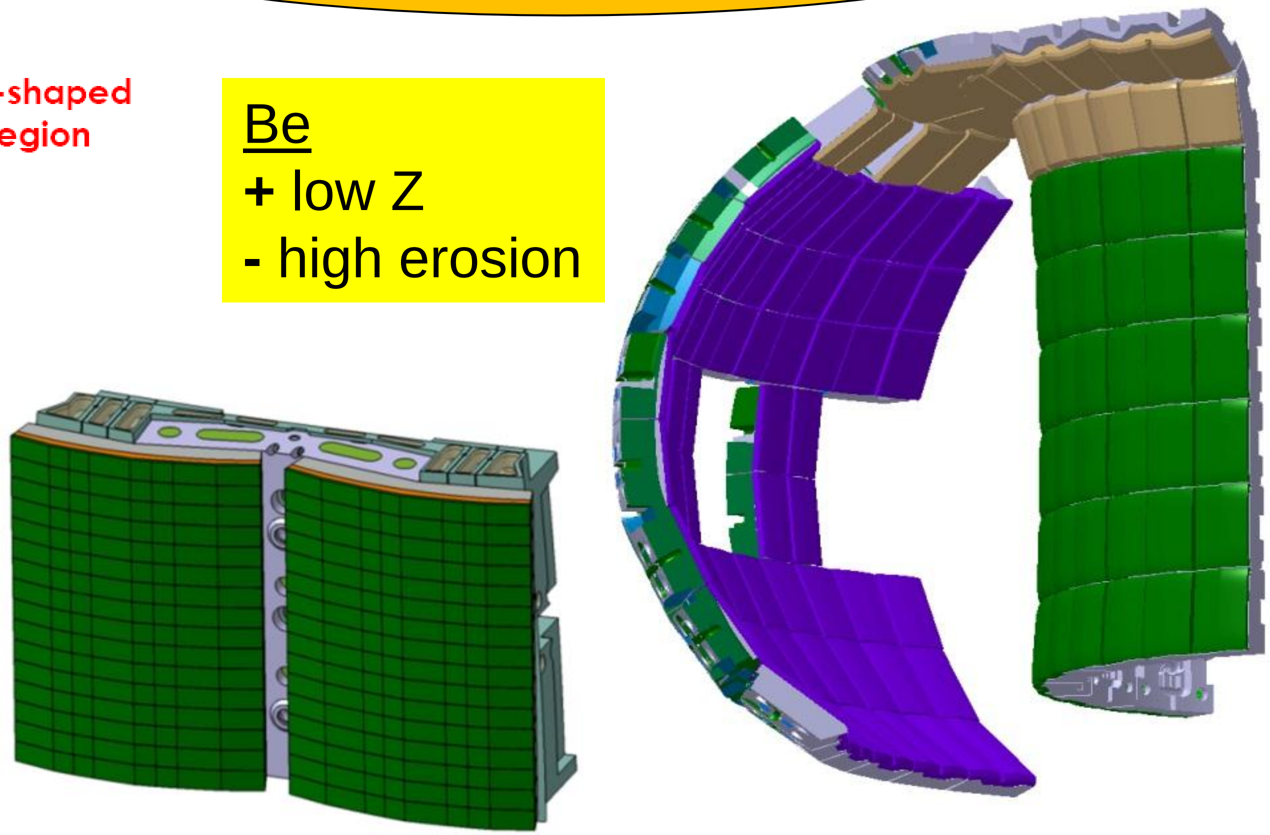
ITER Be wall – BM erosion



FLFS close to 2nd separatrix =>
First PFC ***life time*** estimates assuming limiter-like contact on outboard BM11

Be
+ low Z
- high erosion

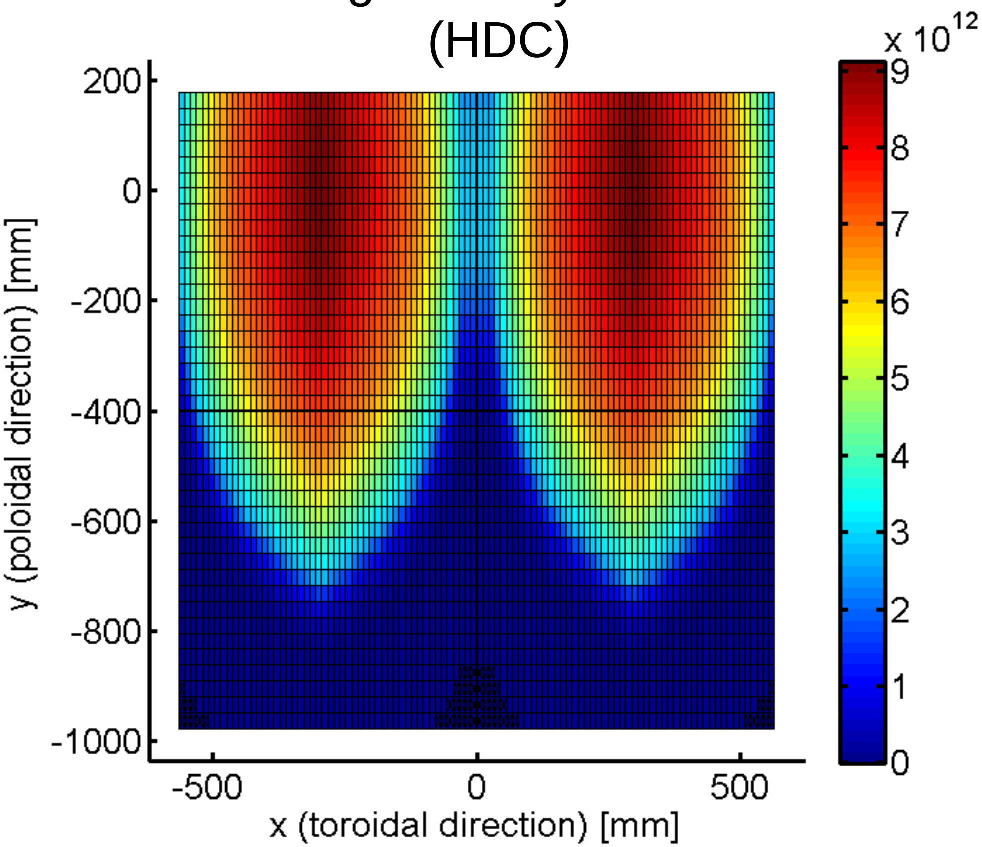


- *Blanket module (BM) shapes optimized for heat loads (P.C.Stangeby)*

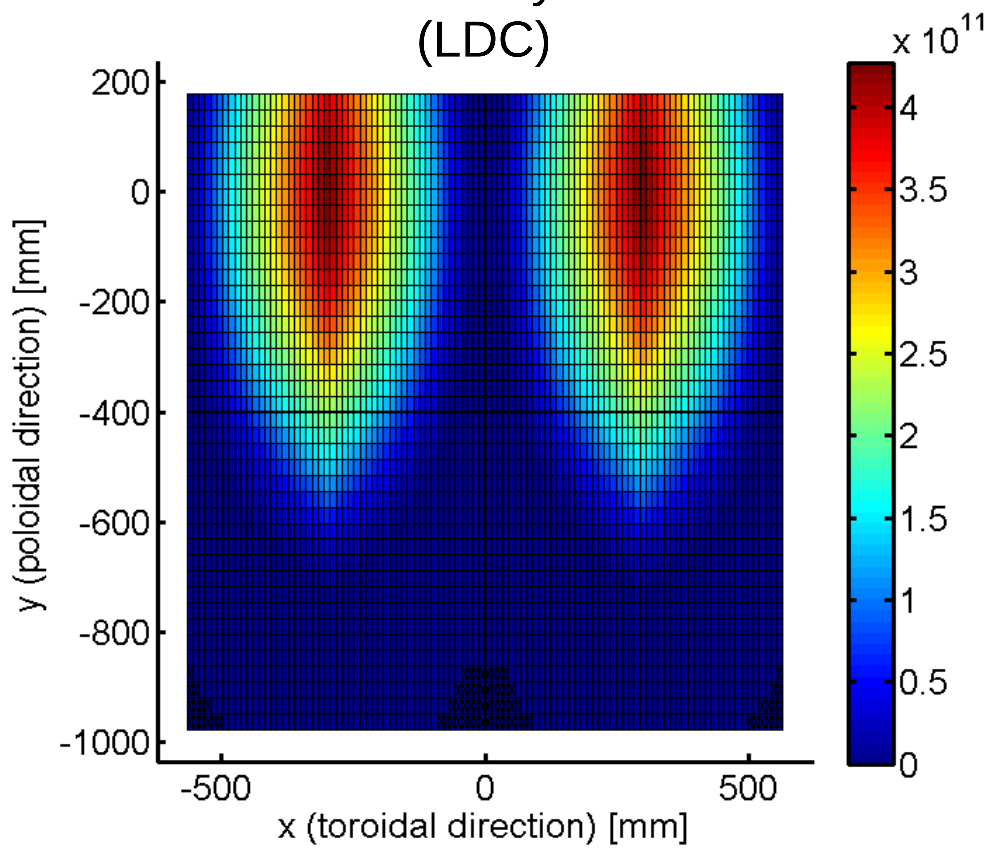
Aim – predictive modelling of ITER, including first wall life time

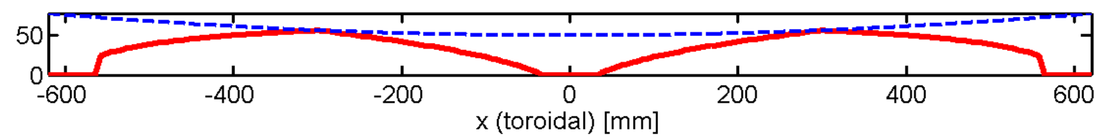
Plasma parameters at limiter surface

High density case (HDC)



Low density case (LDC)

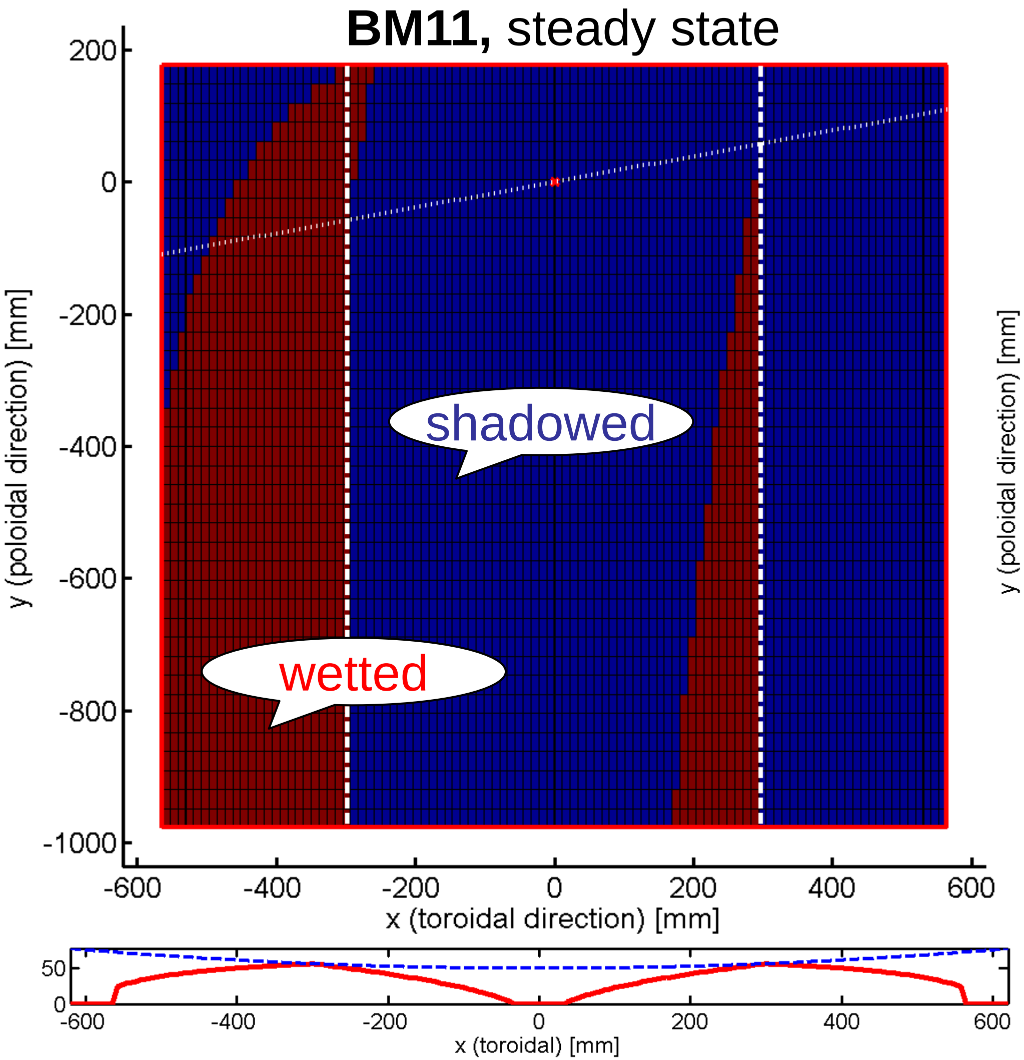


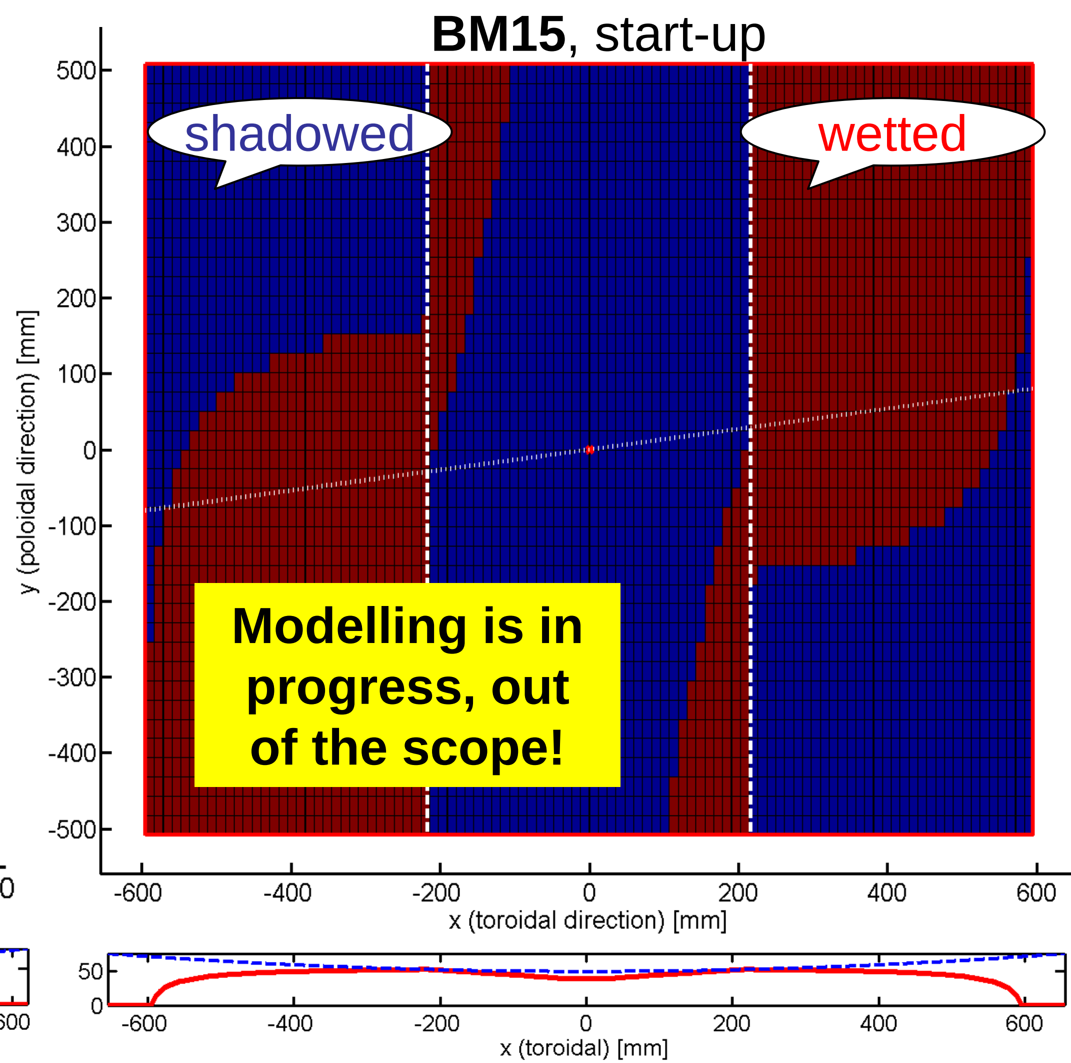


T_e = 10eV = const
T_i = 20eV = const

T_e = 7.1eV = const
T_i = 18.6eV = const

Shadowing patterns (LIM and ERO)

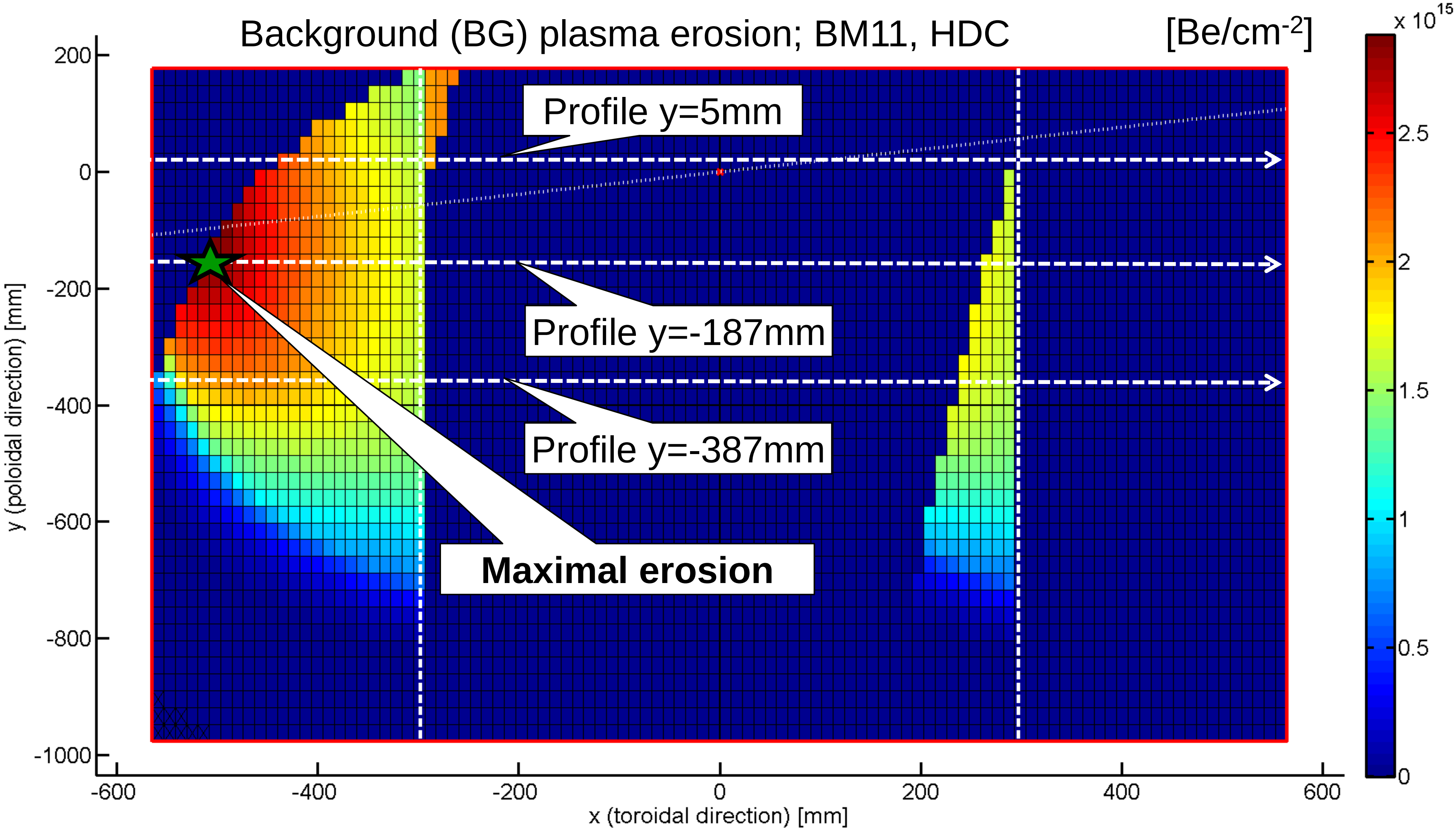




In shadowed areas we assume no BG erosion and re-deposition of intrinsic Be impurity

Shaping and shadowing implemented in the parametric form for any BM

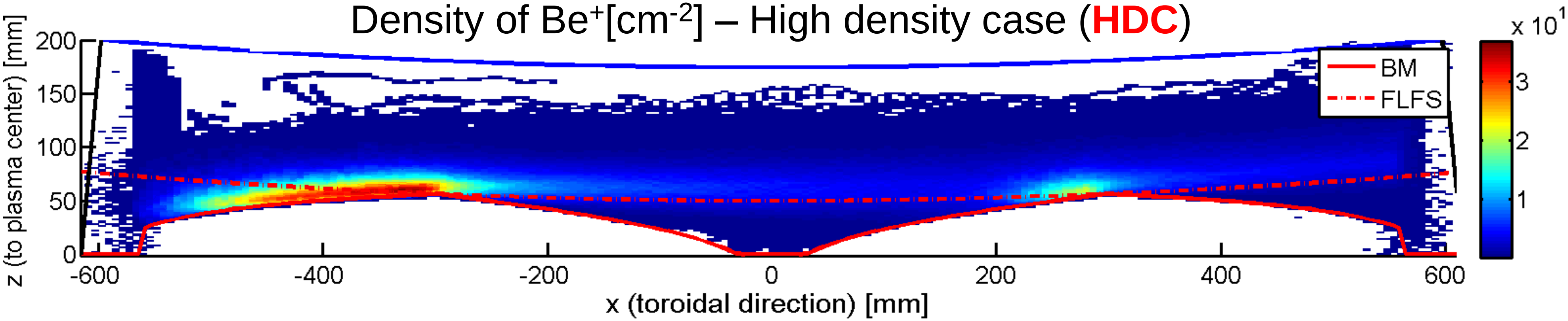
Poloidal positions of toroidal profiles



For LDC the maximal erosion point is elsewhere . . .

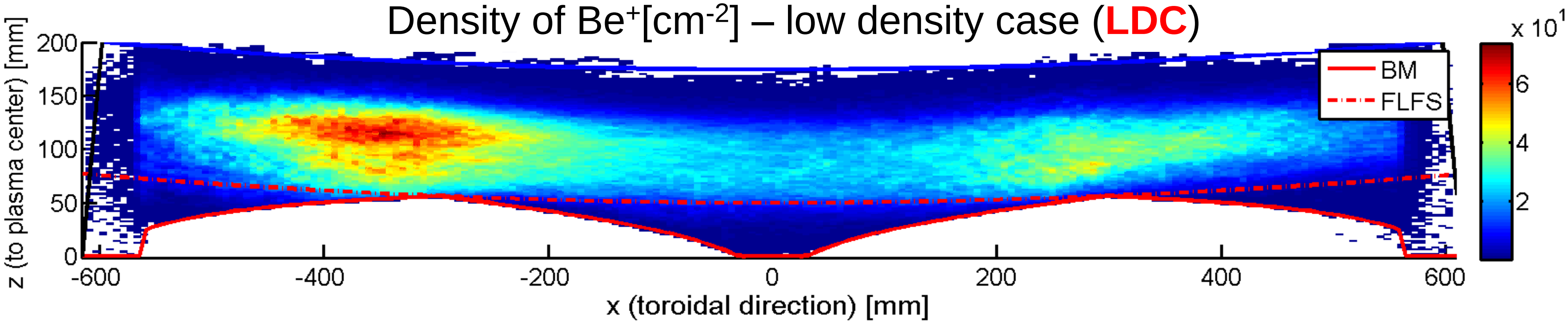
Deposition: low vs. high density plasma

Density of Be^{+}[cm^{-2}] – High density case (**HDC**)



Be is ionized close to surface . . . Large redeposition.

Density of Be^{+}[cm^{-2}] – low density case (**LDC**)

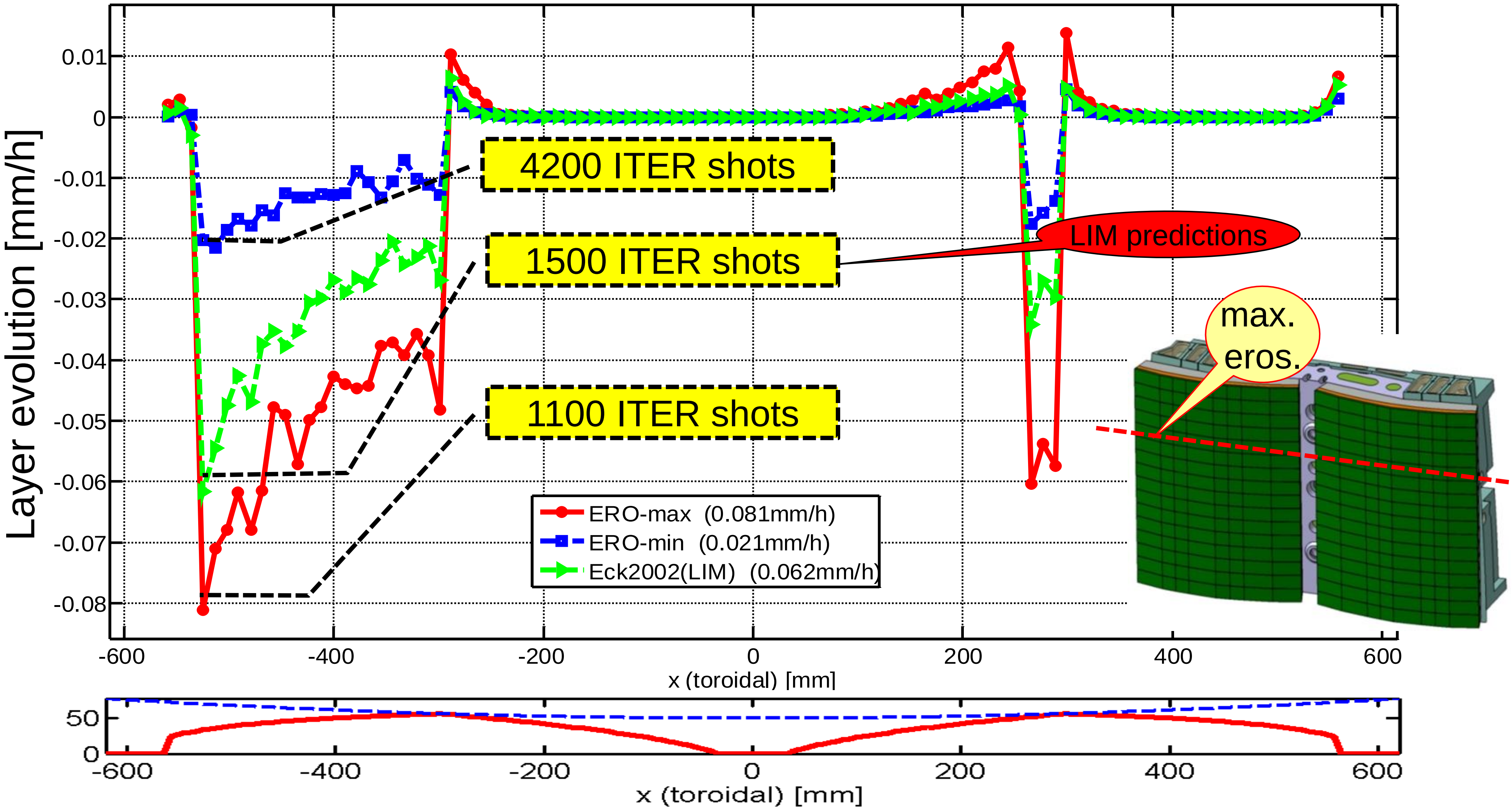


Be is ionized far away from surface . . . Small redeposition.

In both LIM and ERO deposition dependence on plasma parameters is feasible!

Sputter yields assumptions and net erosion

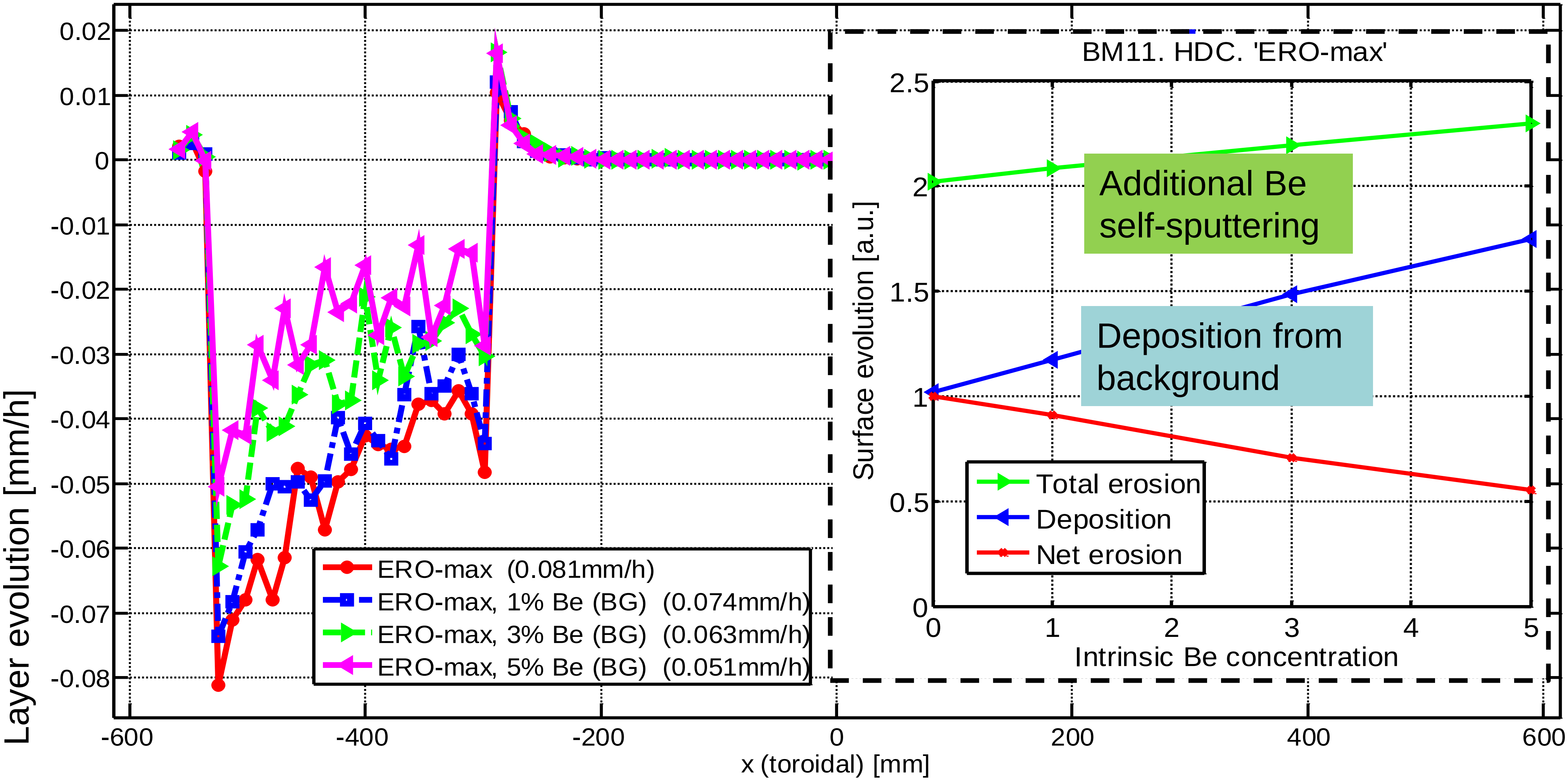
BM11, 'HDC': net erosion (deposition) profile at y=-187mm



The life time is the subject of sputtering yield assumptions!

Intrinsic Be impurity influence on net erosion

BM11, ‘HDC’: net erosion (deposition) profile at y=-187mm



Deposition of Be impurity from plasma dominates over additional Be self-sputtering

D Borodin et al 2011 Phys. Scr. 2011 014008 doi:10.1088/0031-8949/2011/T145/014008

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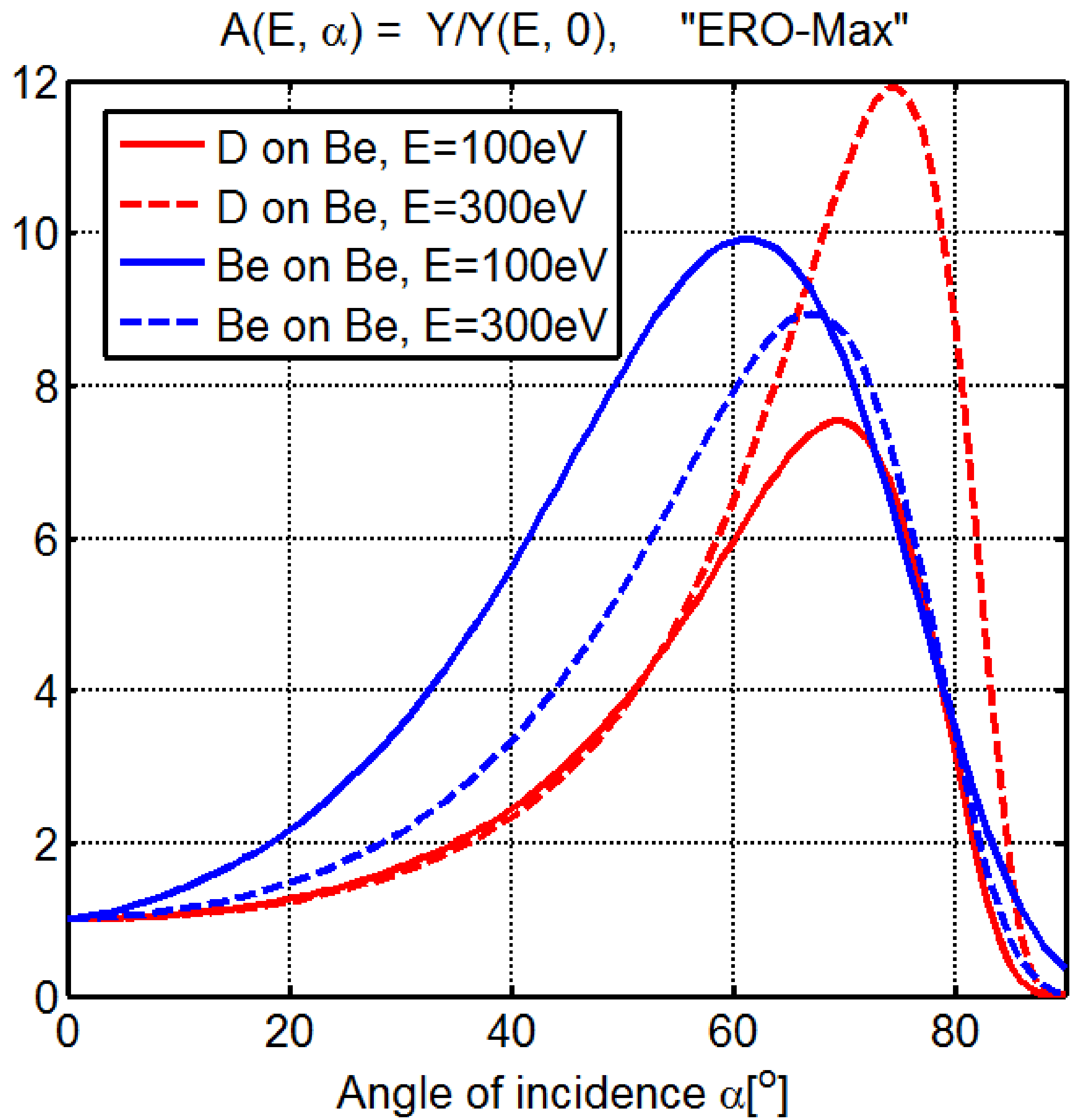
Sputtering: Angular Dependence

Angular part is of importance, however it is difficult to take it into account w/o modelling!

$$Y(E_{in}, \alpha_{in}) = Y(E_{in}, 0) * A(E_{in}, \alpha_{in})$$



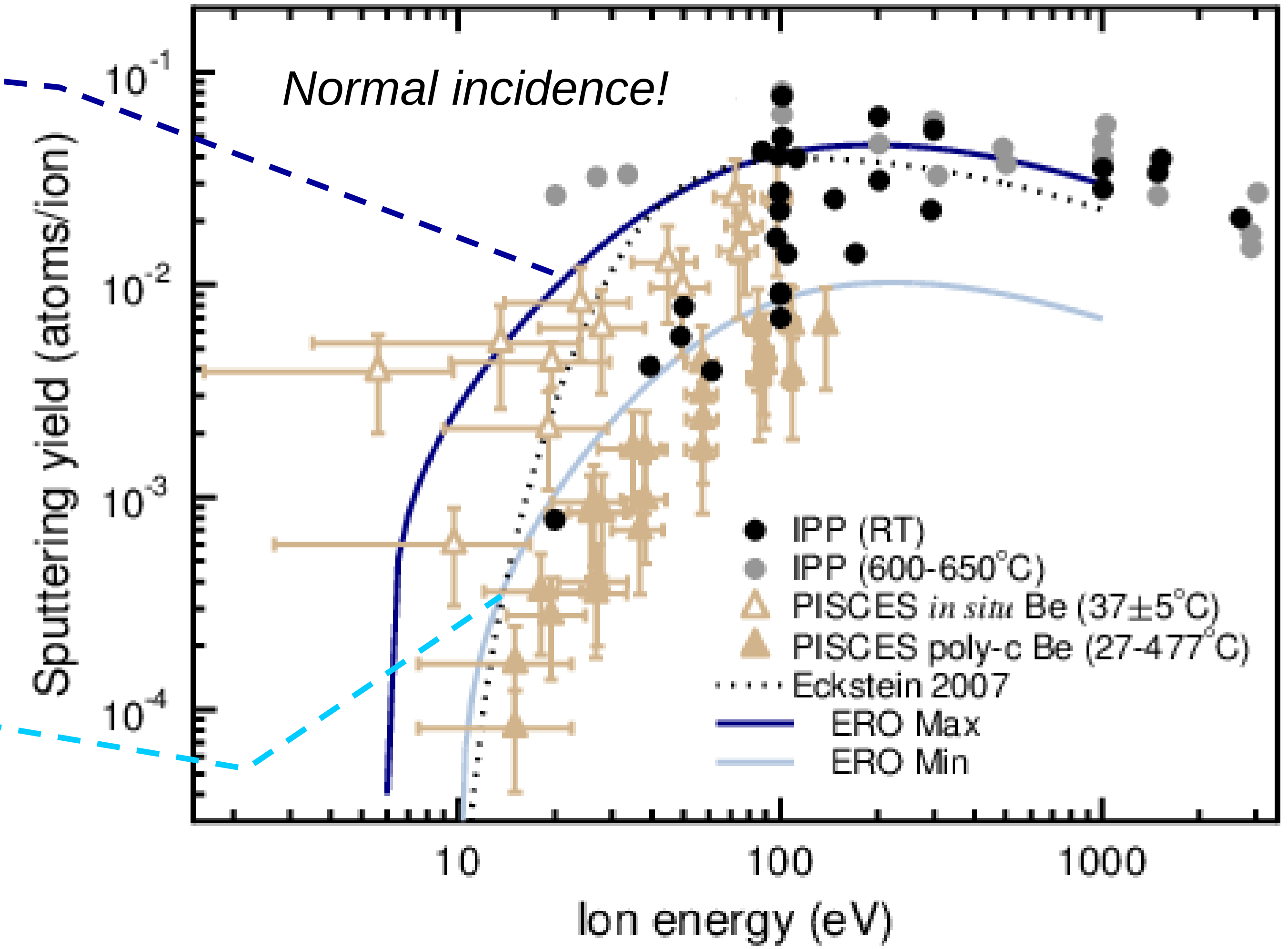
Sputtering data – margin estimates

„ERO-max“
MD + SDTRIMSP
pure Be

Eckstein 2007 fit:
$Y = \mathbf{Y(E_{in}, 0^o)} * A(E_{in}, \alpha_{in})$

„ERO-min“
SDTrimSP
50%Be + 50%D

Be by D^+ sputtering



D. Borodin et al., J. Nucl. Mater. (2013), http://dx.doi.org/10.1016/j.jnucmat.2013.01.043

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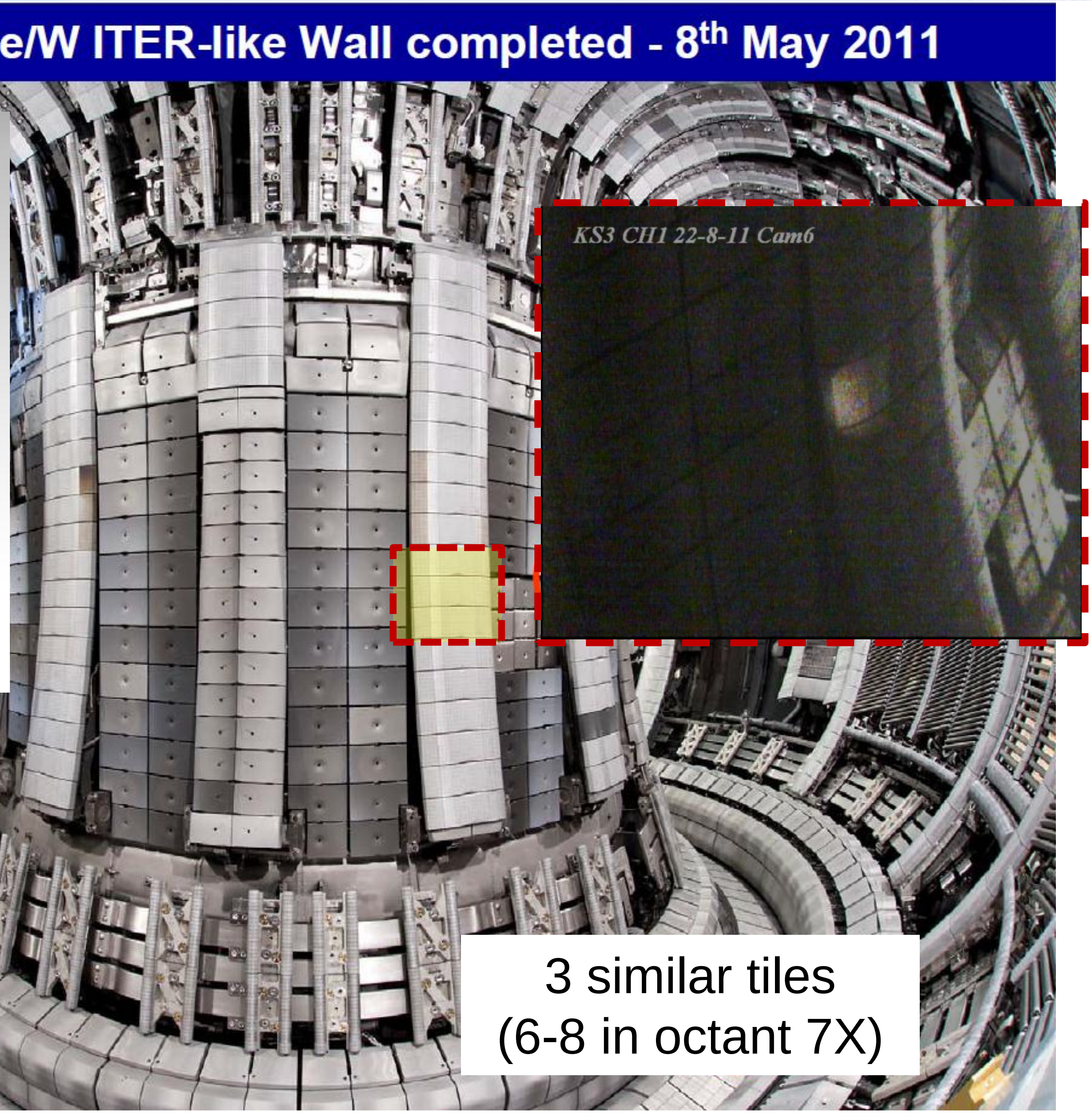
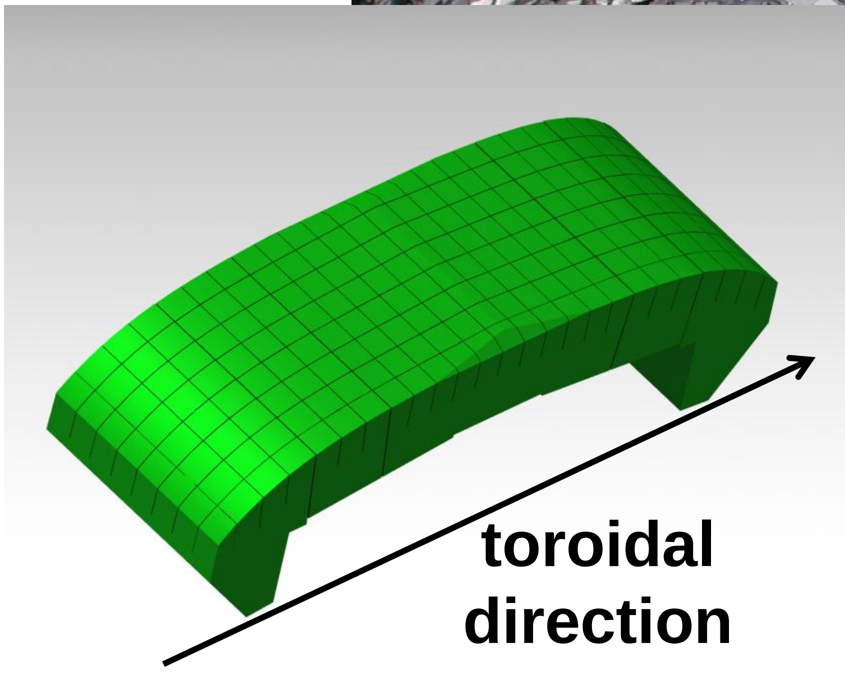
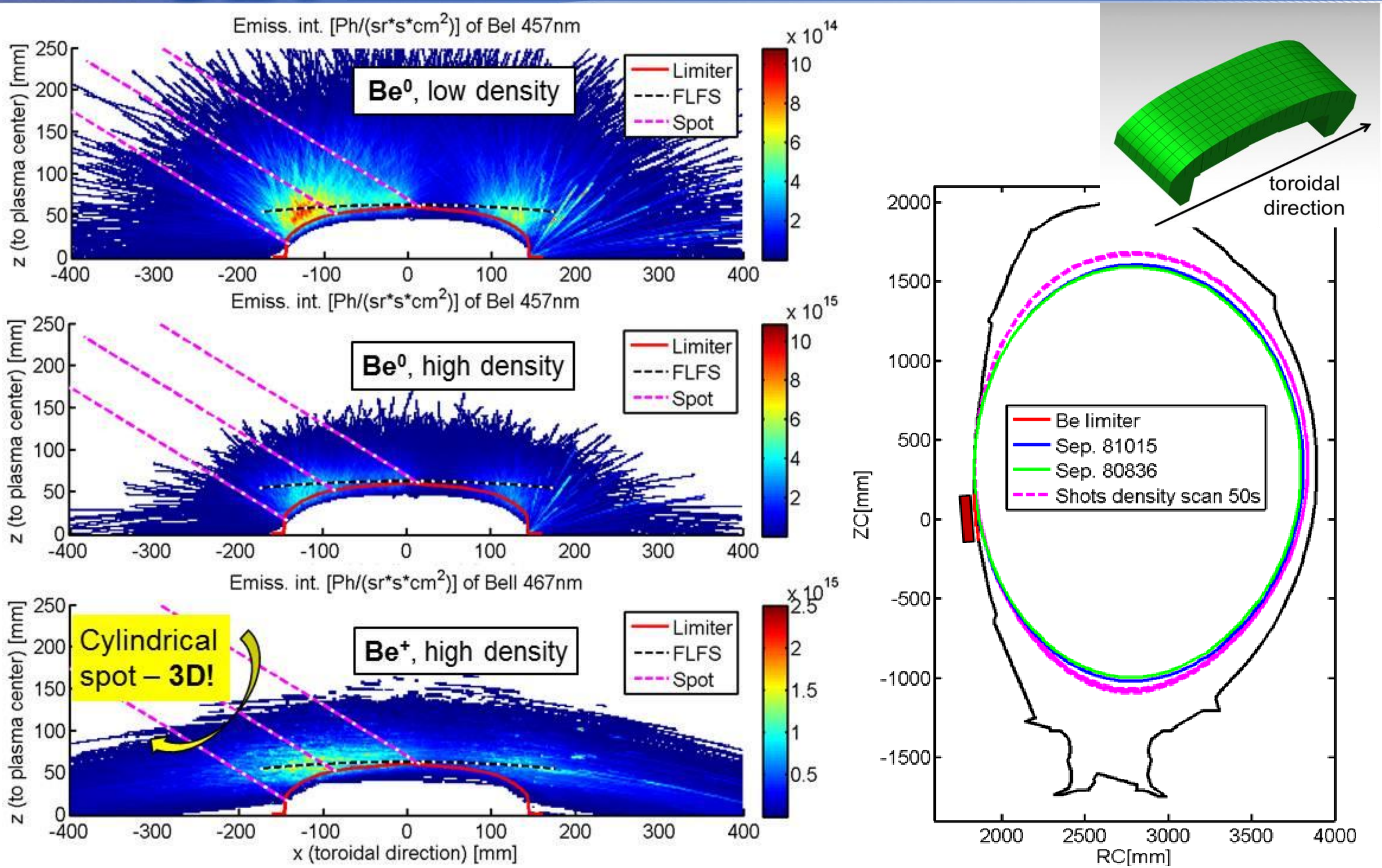
Be limiter tiles position

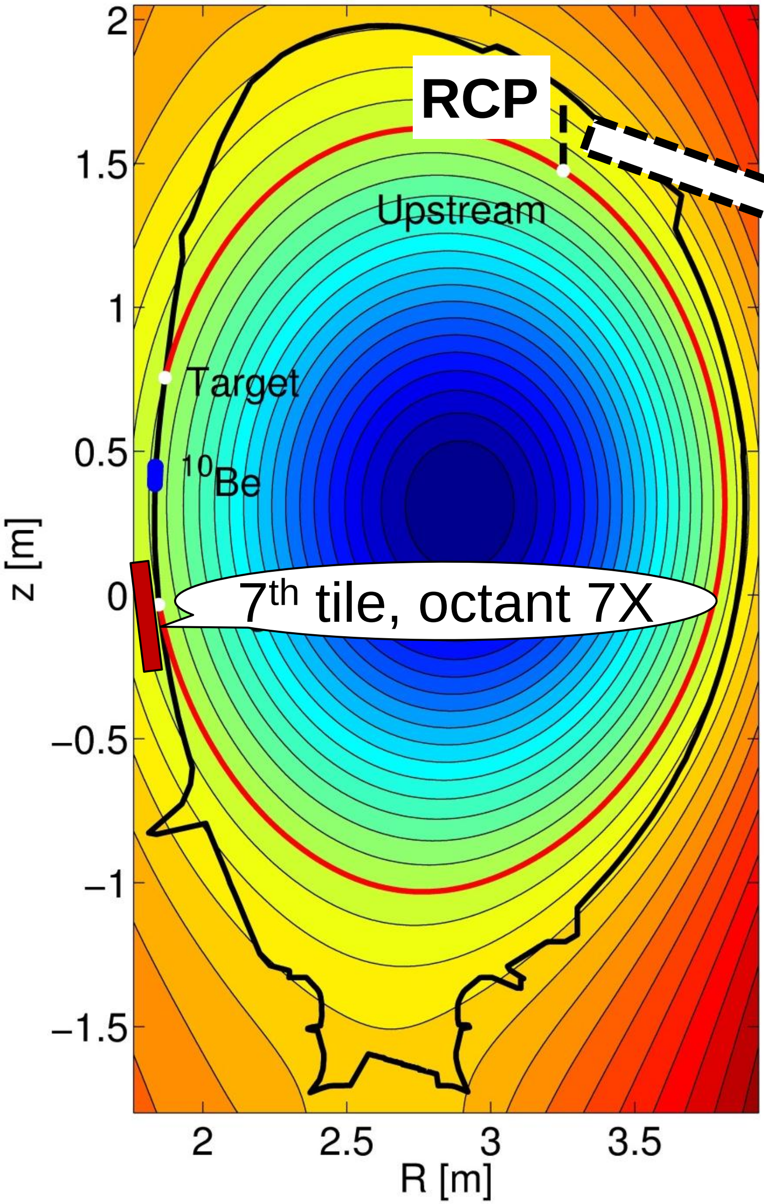


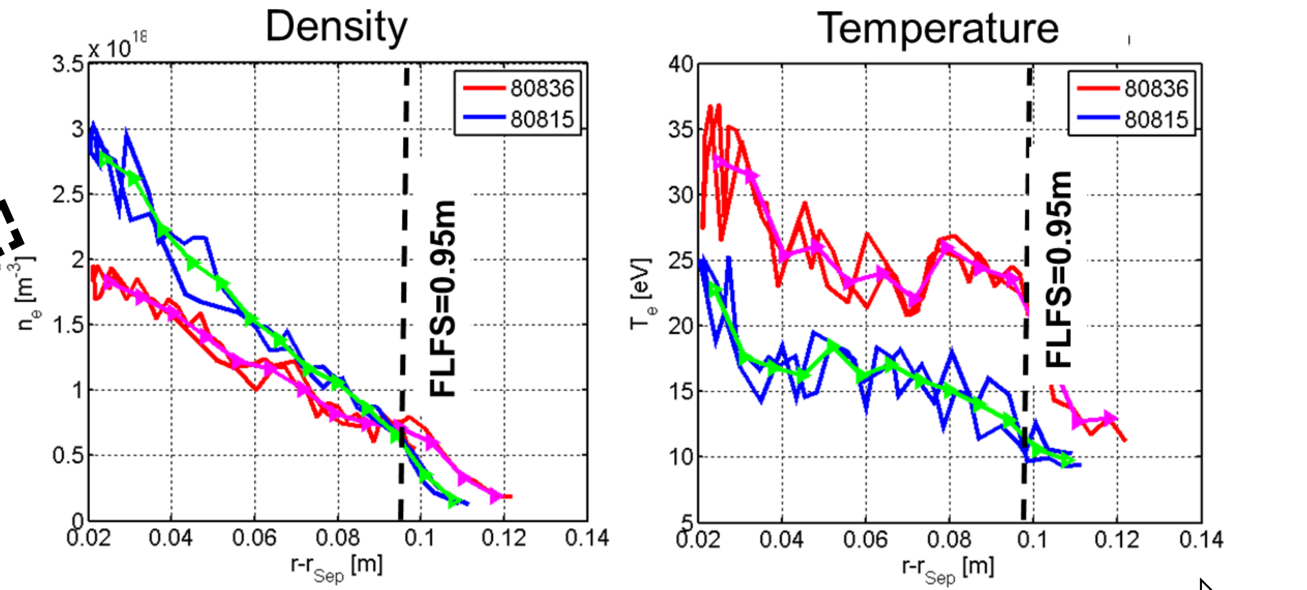


Line-of-sight integration



Plasma parameters (3D)





RCP measurements mapped in 2D

- *2-point model as first approach for limiter plasma*

J.Miettunen PSI-2012

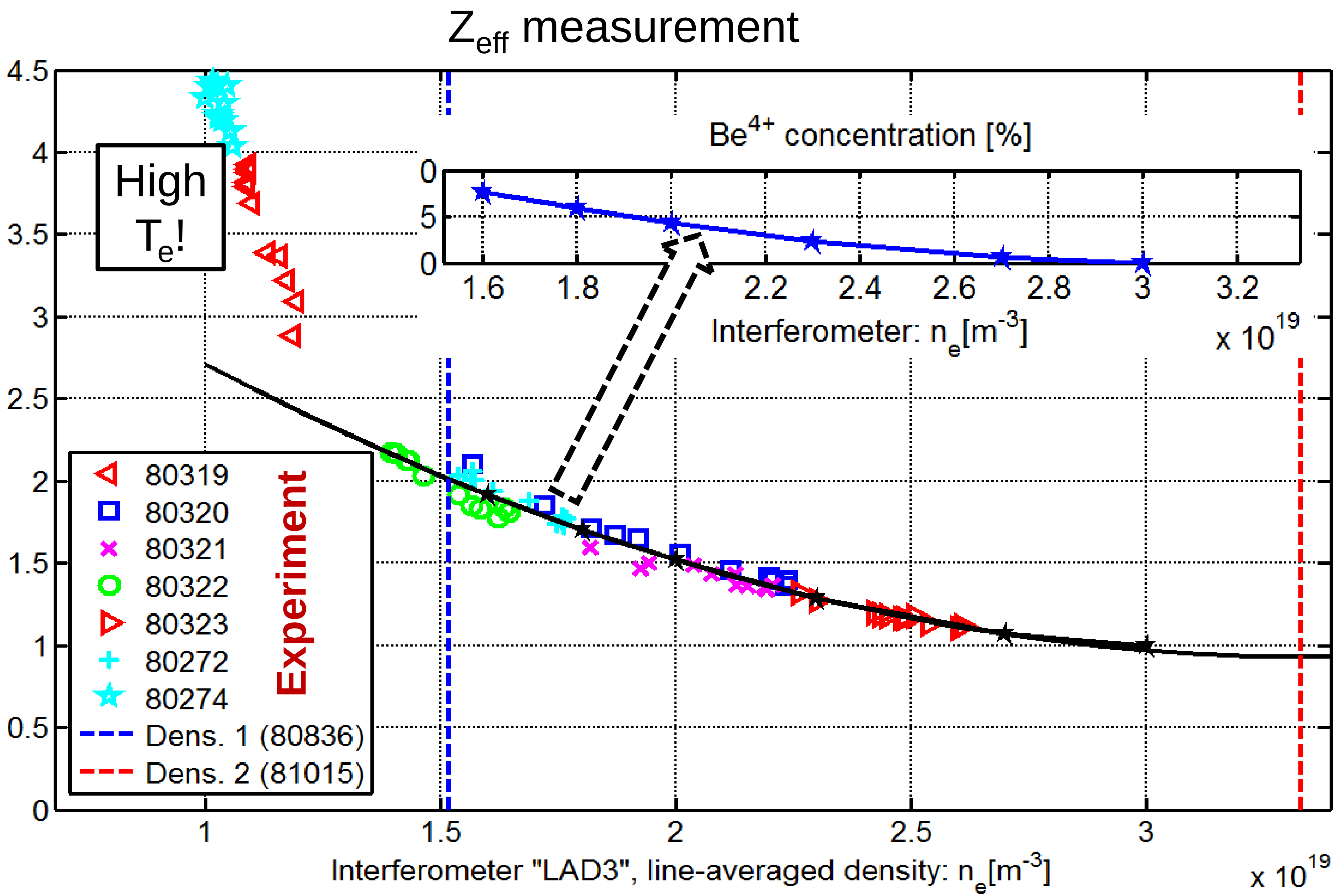
ERO assumes toroidal symmetry to get 3D . .

Mapping only for 2 shots using line-averaged interferometer density as a cross-reference

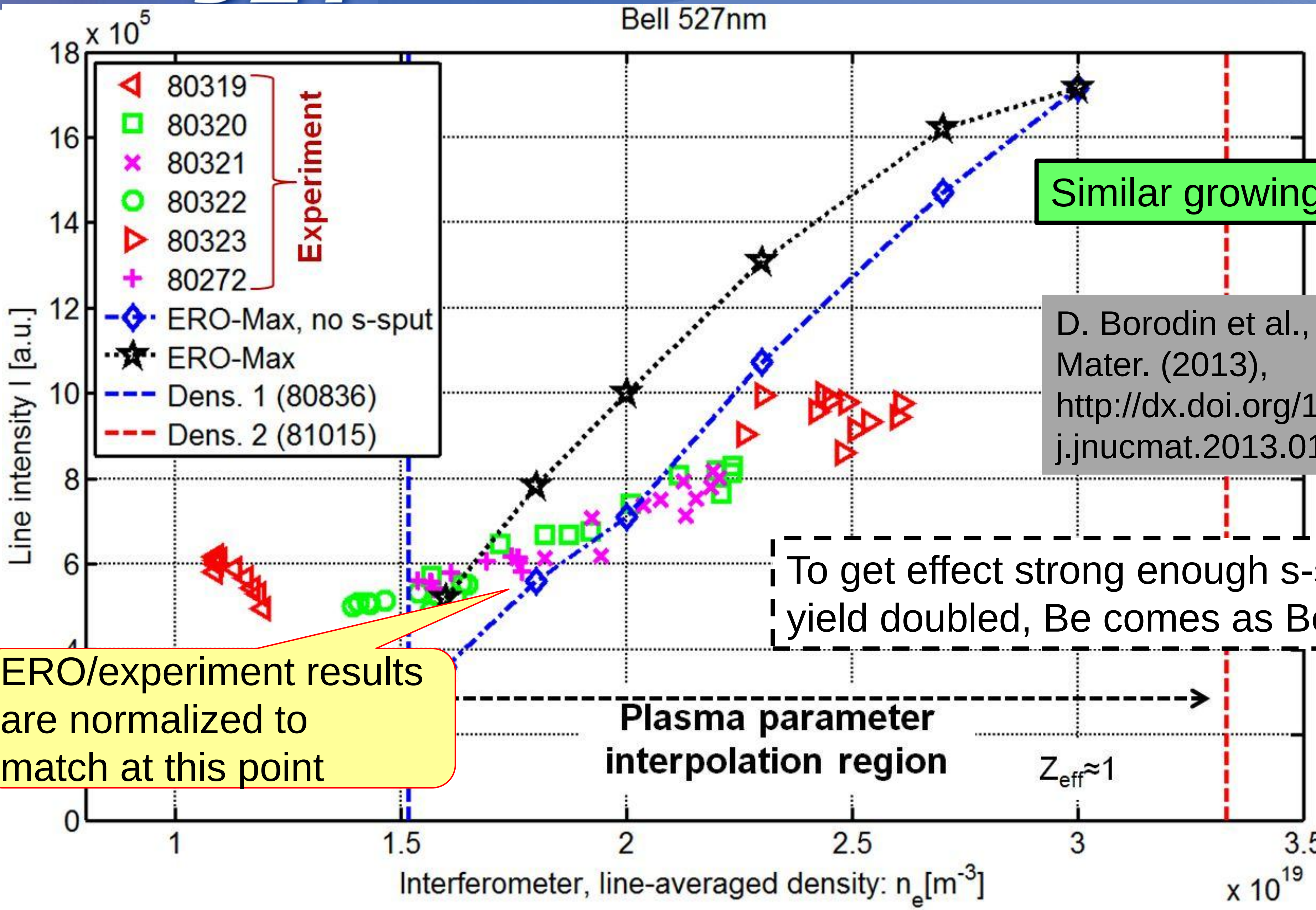
- $<1.5*10^{19}m^{-2}$ „low density case“
- $>3.3*10^{19}m^{-2}$ „high density case“

Density scan: liniar interpolation

Be intrinsic impurity



ERO&Experiment: Bell light



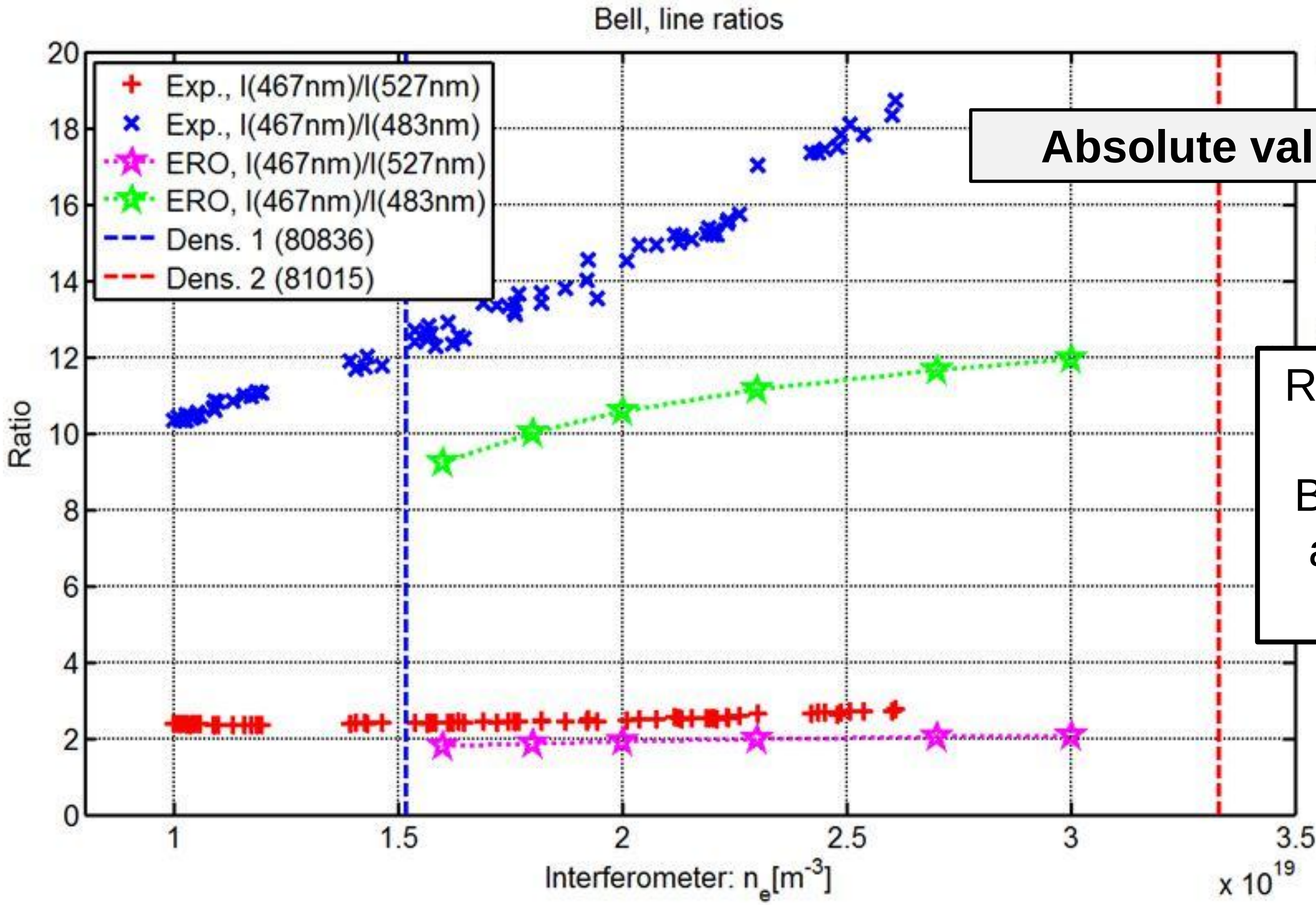
Similar growing trend!

D. Borodin et al., J. Nucl. Mater. (2013), http://dx.doi.org/10.1016/j.jnucmat.2013.01.043

To get effect strong enough s-sputter yield doubled, Be comes as Be^{3+} . . .

ERO/experiment results are normalized to match at this point

ERO&Experiment: BeII line ratios



Absolute values!

Ratios inside BeI and BeI/BeII are also within factor 2!

Indicates that atomic data (ADAS '96') and simulated Be transport (3D density pattern) are reasonable!

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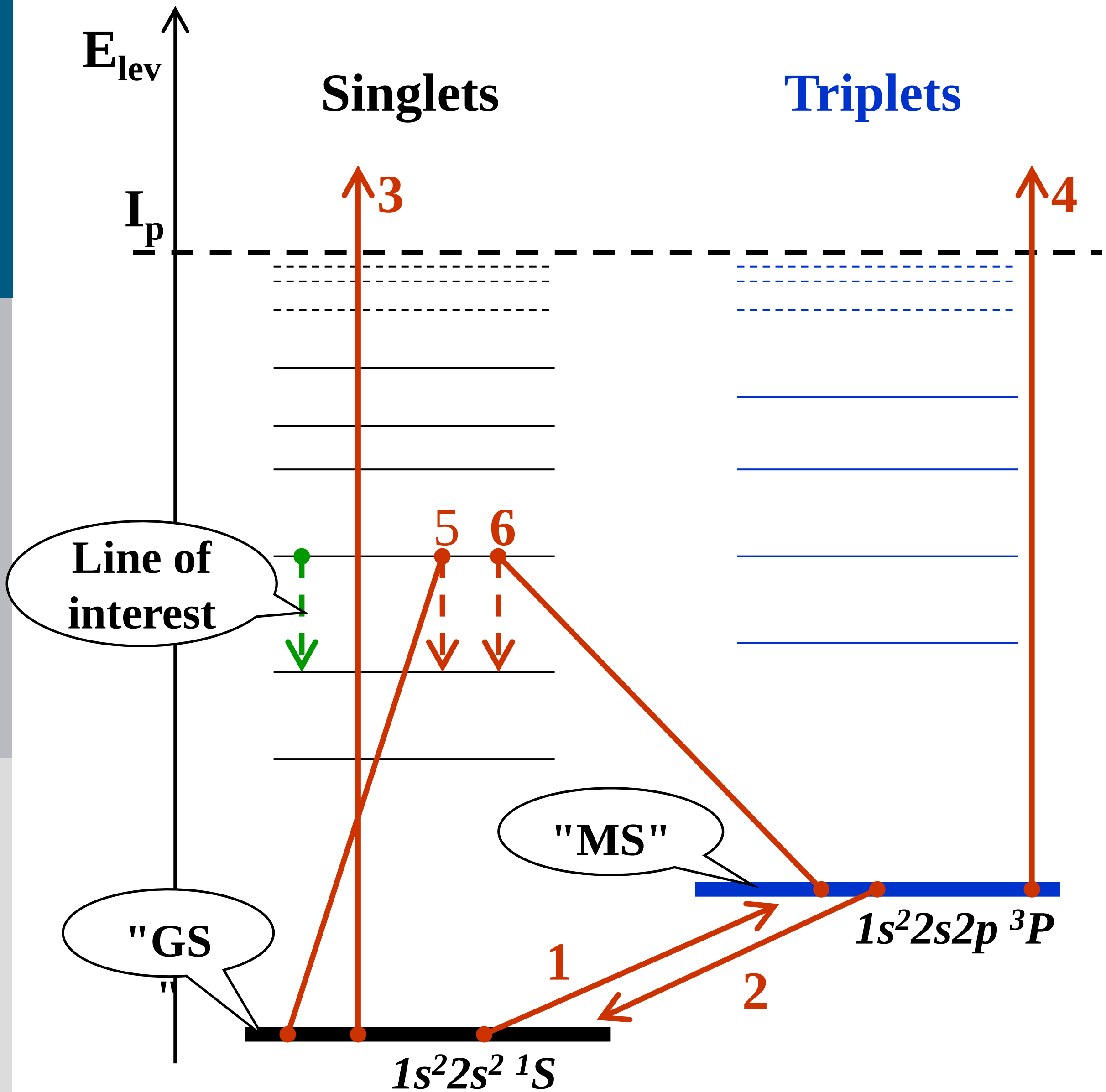
BeI – 1 MS approximation scheme



Effective rates:

1) <ExGM> - excitation from "GS" to "MS"

2) <ExMG> - deexcitation from "MS" to "GS"

3) <IzG> - ionization from "GS"

4) <IzM> - ionization from "MS"

5) <IG> - line intensity (PEC – photon emission coefficient), contribution from "GS"

6) <IM> - PEC, contrib. from "MS"

5, 6 are individual for every line of interest!

Line intensities – dynamic approach

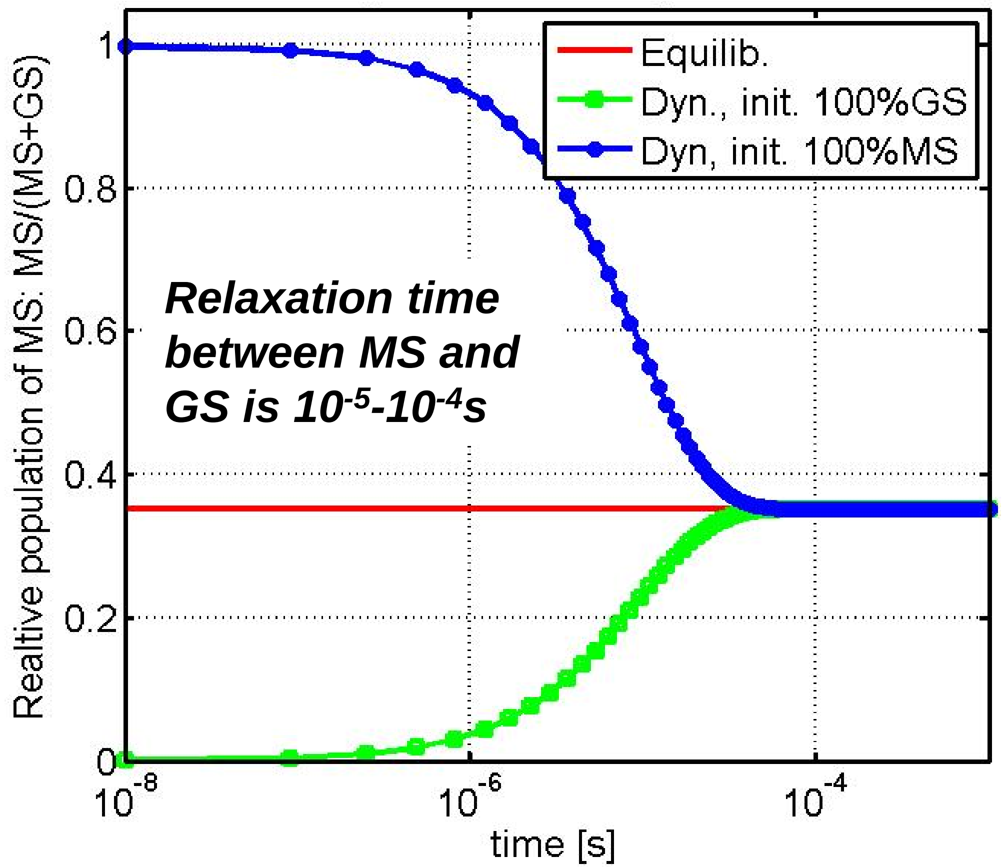
$$\begin{cases} \dfrac{dN_{GS}}{dt} = -\langle ExGM \rangle N_{GS} - \langle IzG \rangle N_{GS} + \langle ExMG \rangle N_{MS} \\ \dfrac{dN_{MS}}{dt} = -\langle ExMG \rangle N_{MS} - \langle IzM \rangle N_{MS} + \langle ExGM \rangle N_{GS} \end{cases}$$

Analytical solution

$(C_{1i}, C_{2i}, \lambda_p, \lambda_m$ determined by rates$)$:

$$dN_i(t) = C_{1i} \exp(-\lambda_p t) + C_{2i} \exp(-\lambda_m t)$$

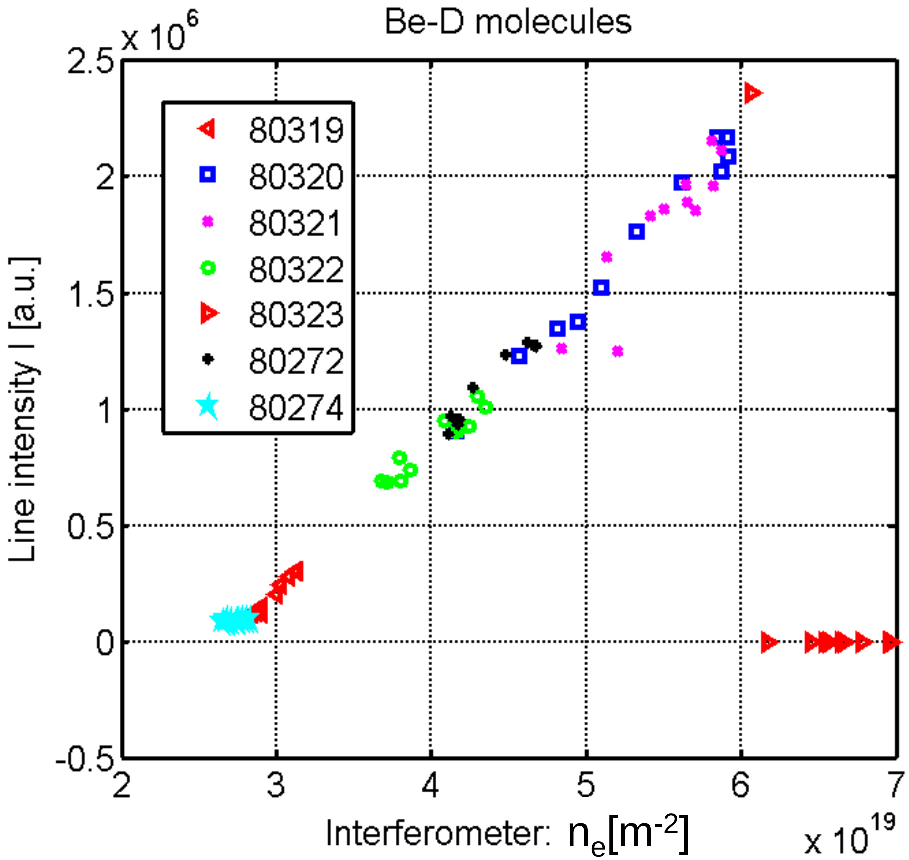
ADAS; T_e=1eV, n_e=2*10^{12}cm^{-3}

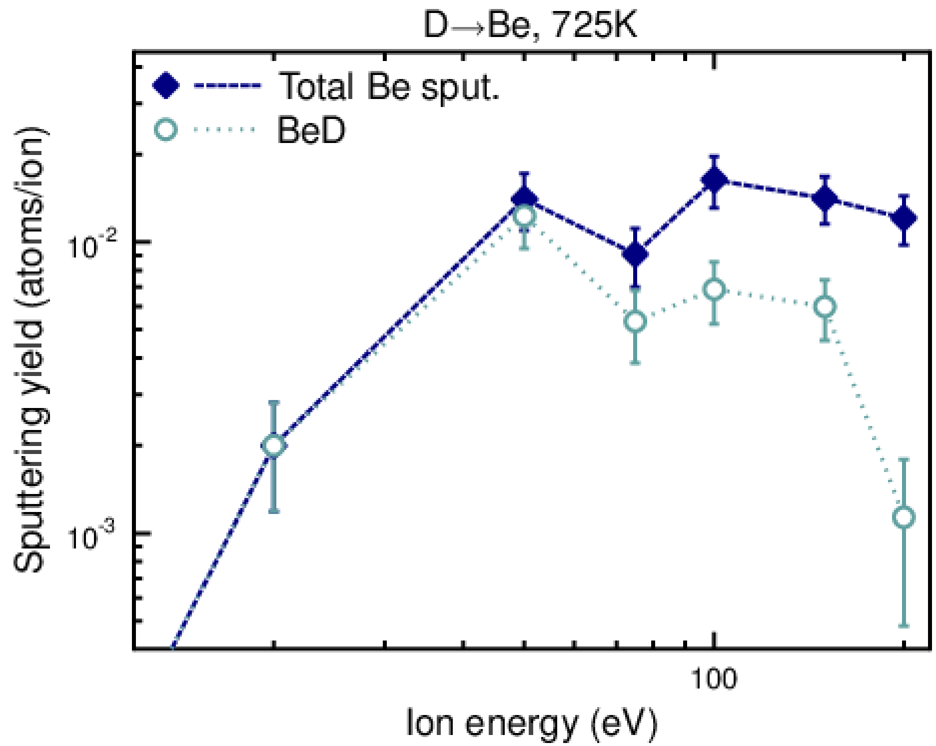


MS resolved approach

- *allows to treat effectively the slow relaxation between triplet and singlet levels*
- *important if MS population affected by extra processes and at high plasma parameter gradients*

Be-D molecules



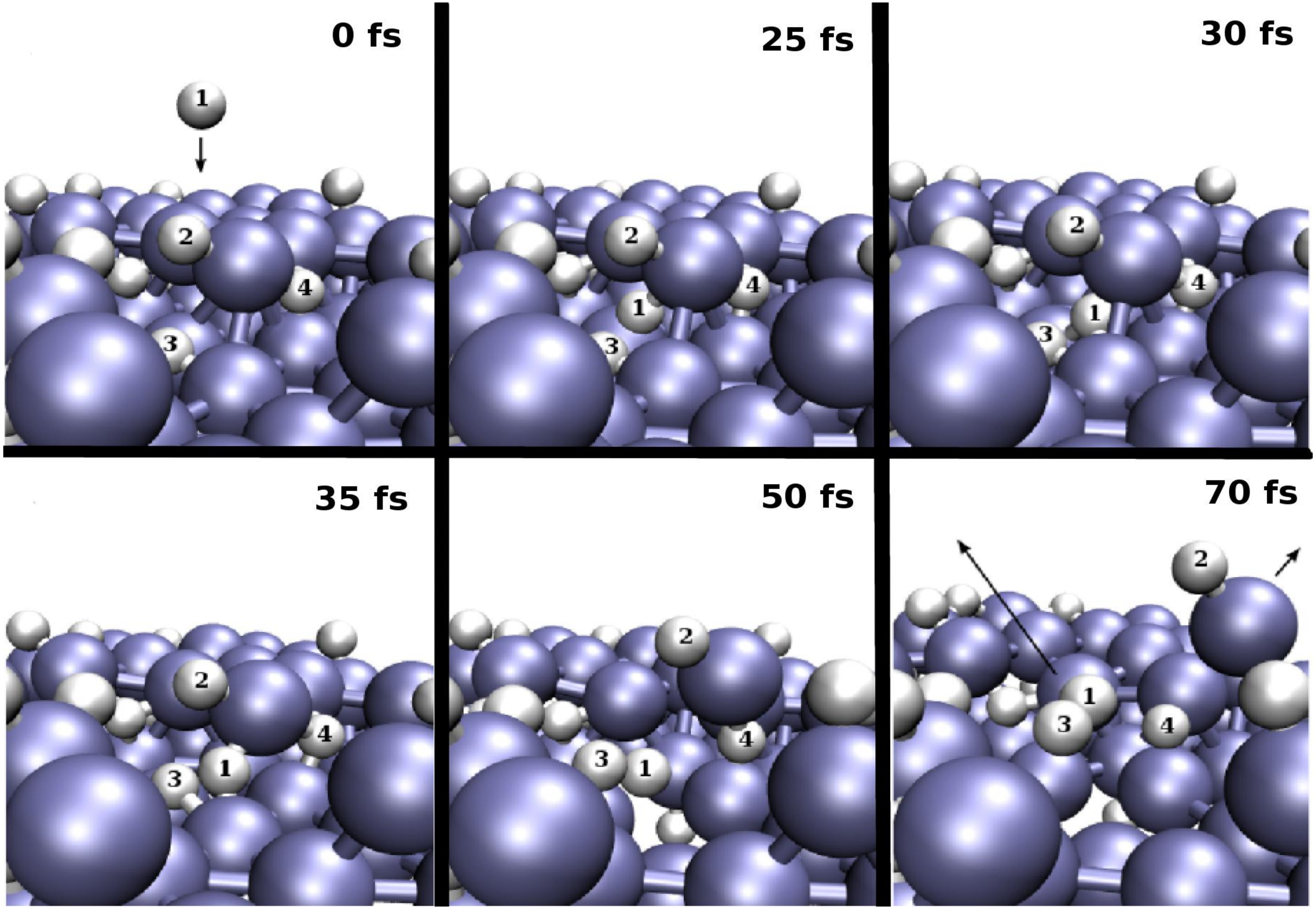


Be-D implementation in ERO –
C.Bjoerkas et al, PSI-2012

May act as an important release mechanism, affecting other intesities ! . .
Further consideration is necessary.

Swift chemical sputtering

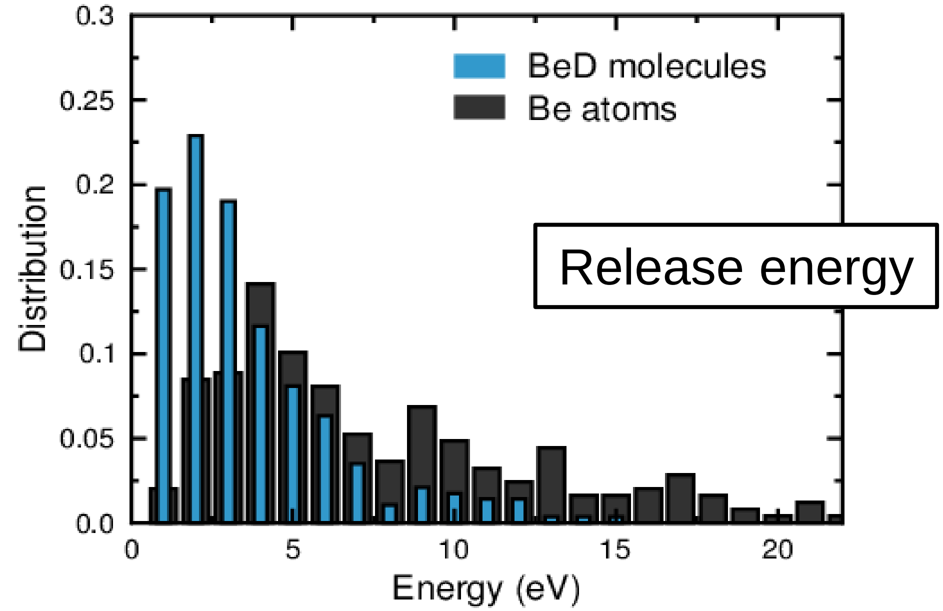
Snapshots of a single sputtering as an illustration for MD simulation

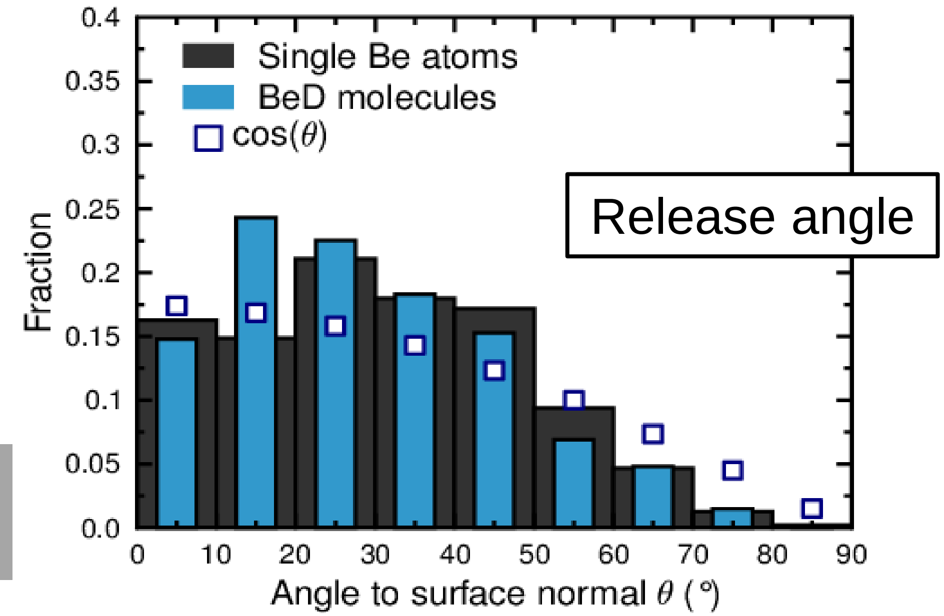


BeD implementation in ERO

- BeD yield:
  - 17% of total Be sputtering yield assumed in benchmark simulations for PISCES-B [*].
  - If surface T controlled, BeD fraction is ion energy dependent
- Sputtering and reflection:
  - MD: BeD sputters as single Be and has a low sticking
- Reactions in plasma:
  - BeD + e^- collision rates calculated

[*] C. Björkas et al., J. Nucl. Mater. (2013), http://dx.doi.org/10.1016/j.jnucmat.2013.01.039





ERO input: BeD reactions in plasma

- BeD + e^- collision rates depend on T_e and vibrational state v
  - Assume v=1 and transitions Δv=0

Thanks for consultation to R.Janev

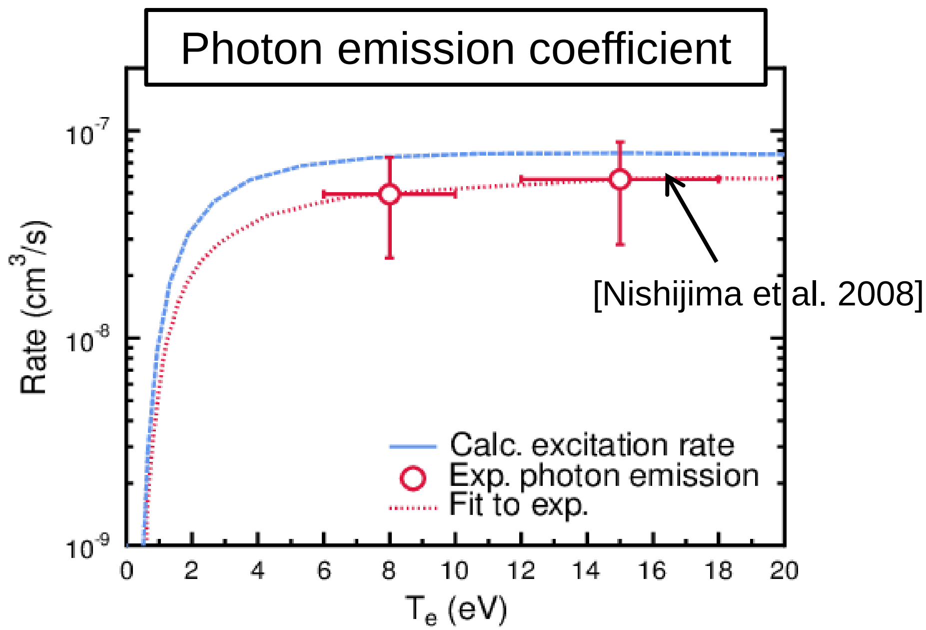
Important reactions

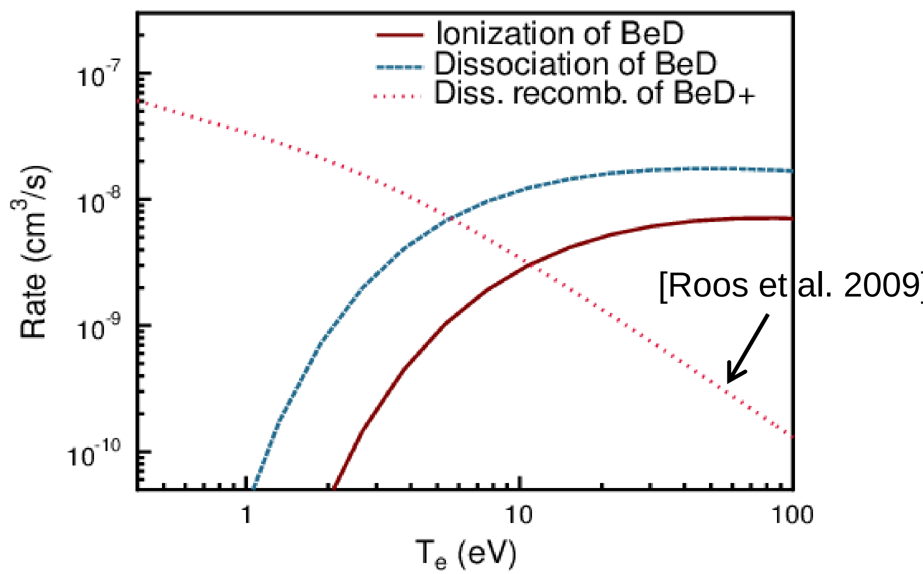
$$e + \mathrm{BeD} \rightarrow e + \mathrm{BeD}^+$$

$$e + \mathrm{BeD} \rightarrow e + \mathrm{BeD}^*$$

$$e + \mathrm{BeD} \rightarrow$$
$$e + \mathrm{BeD}^* \rightarrow e + \mathrm{Be}(3_P)+\mathrm{D}(1_S)$$

Metastable now!





Summary

1. The Be spectroscopy near ILW during density scan can be used for testing of Be sputtering data and modelling assumptions in the ERO code.
2. The ERO code can be used for an extrapolation of the obtained knowledge for ITER and the duty cycle planning.

<u>Outlook</u>

1. Improvement of ERO input data concerning plasma parameter is ongoing
2. The Be impurity should be studied not on the basis of Z_{eff} measurement, but rather using 'periodic boundary' approach.
3. The angle and velocity distributions of both D and Be particles should be taken into the account by calculation of the physical sputtering.
4. Absolute calibrated experimental data should be compared with simulations.
5. Be-D spectroscopy should be simulated in addition to BeI, BeII.
6. ITER predictions should be revised (e.g. new ITER simulations for BM with W).

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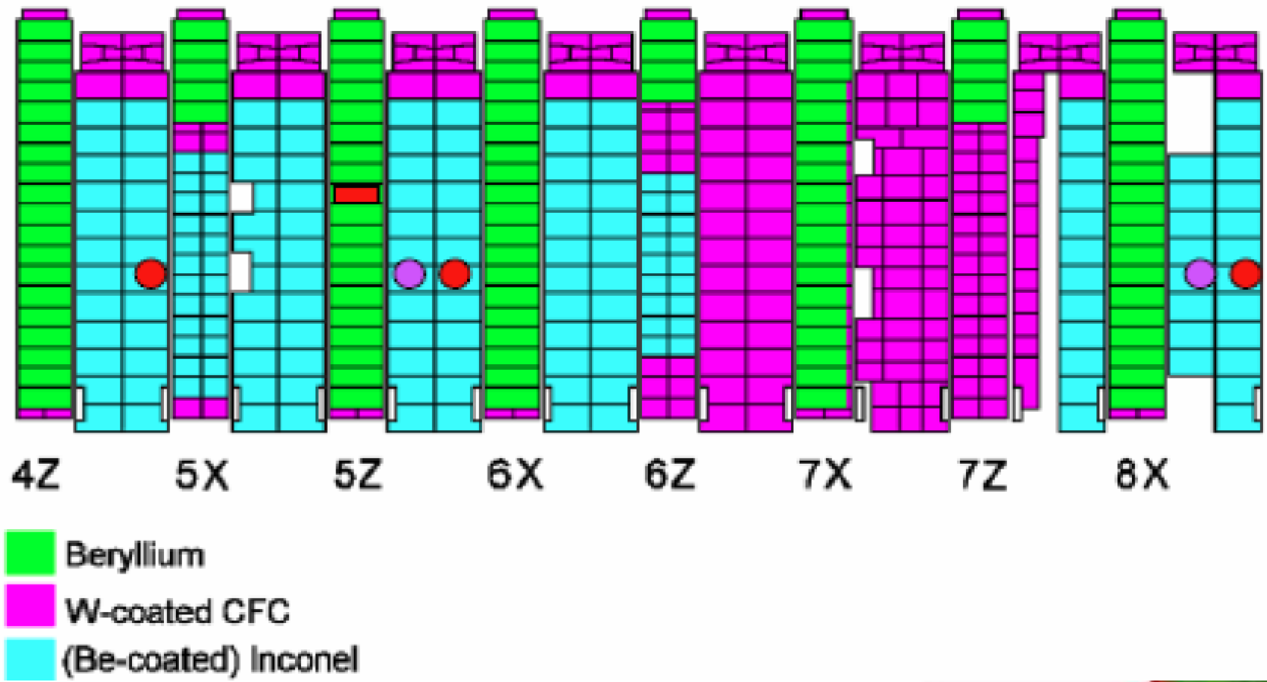
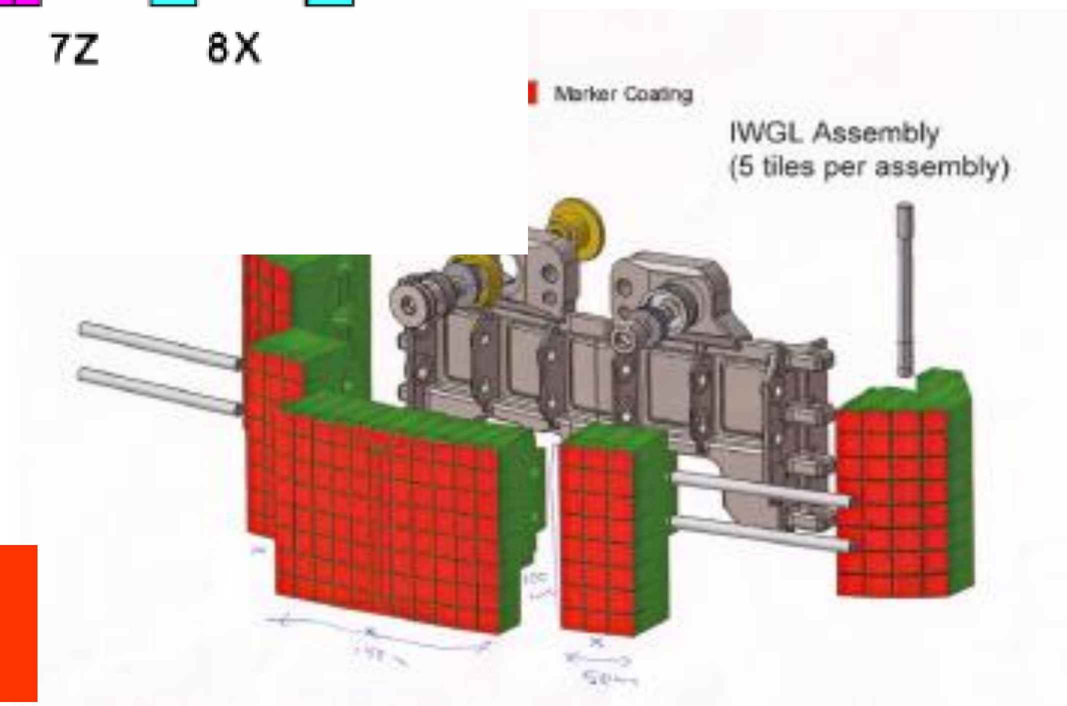
^{10}Be experiment – local transport study



Experiment coordinated by **H. Bergsåker**

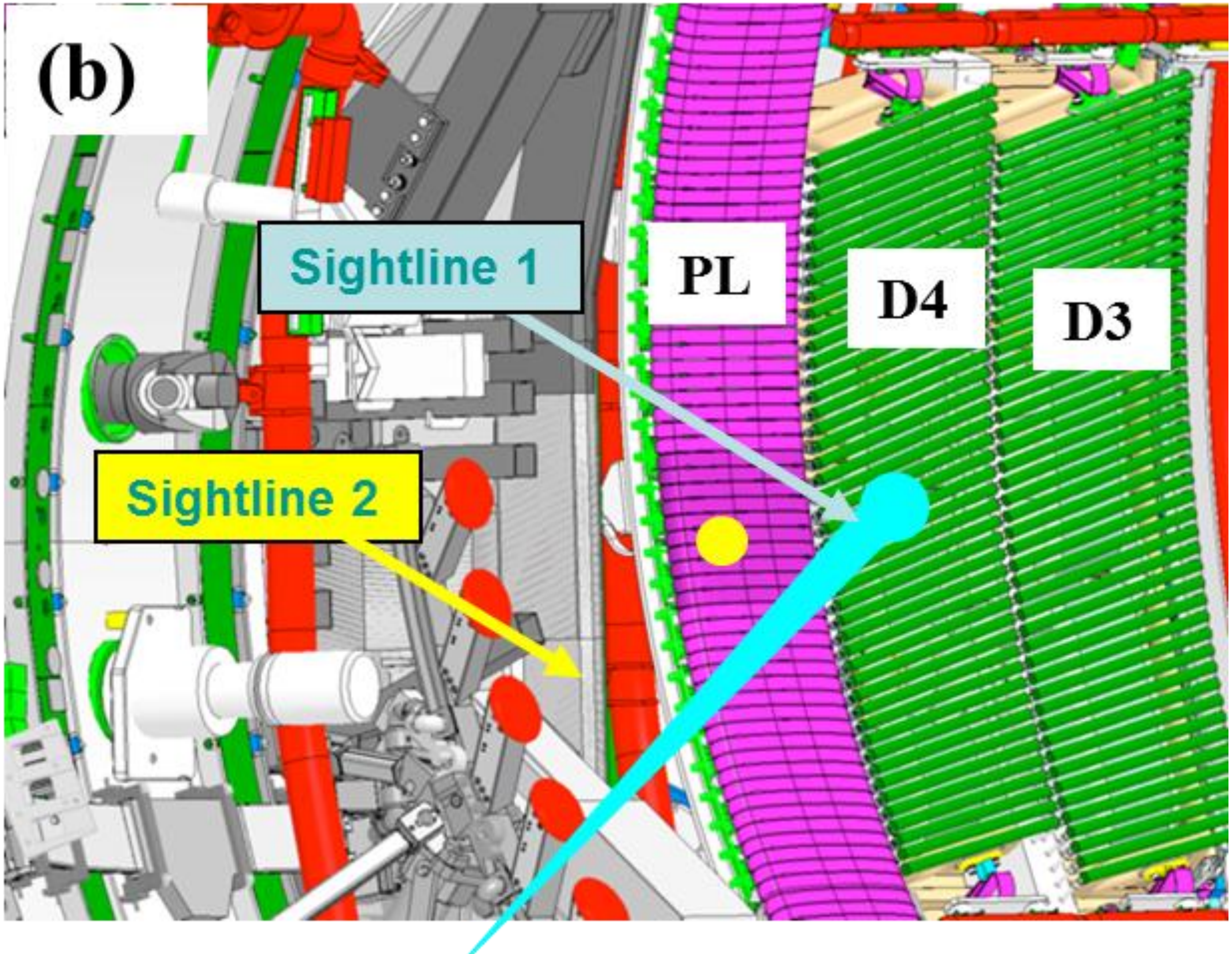


Redeposition on the „wings“
Benchmark for ERO (similar geometry, plasma conditions, etc.)

Long-term exposure to various plasmas . . . uneasy interpretation!

J. Miettunen et al., J. Nucl. Mater. (2013), http://dx.doi.org/10.1016/j.jnucmat.2013.01.128

Be ICRH antena erosion

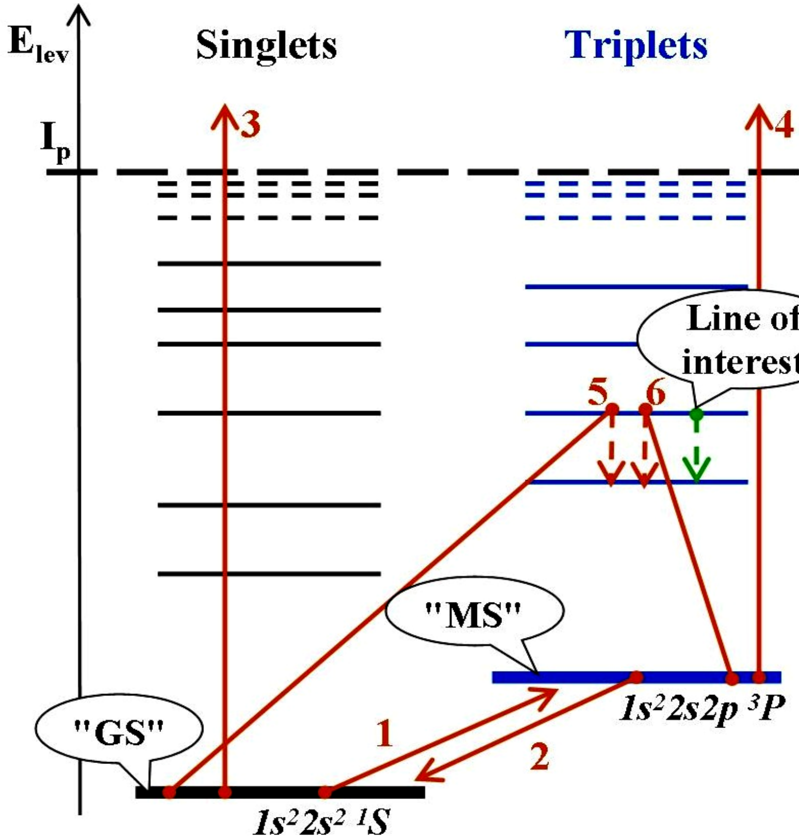


Experiment coordinated by **C.C.Klepper**

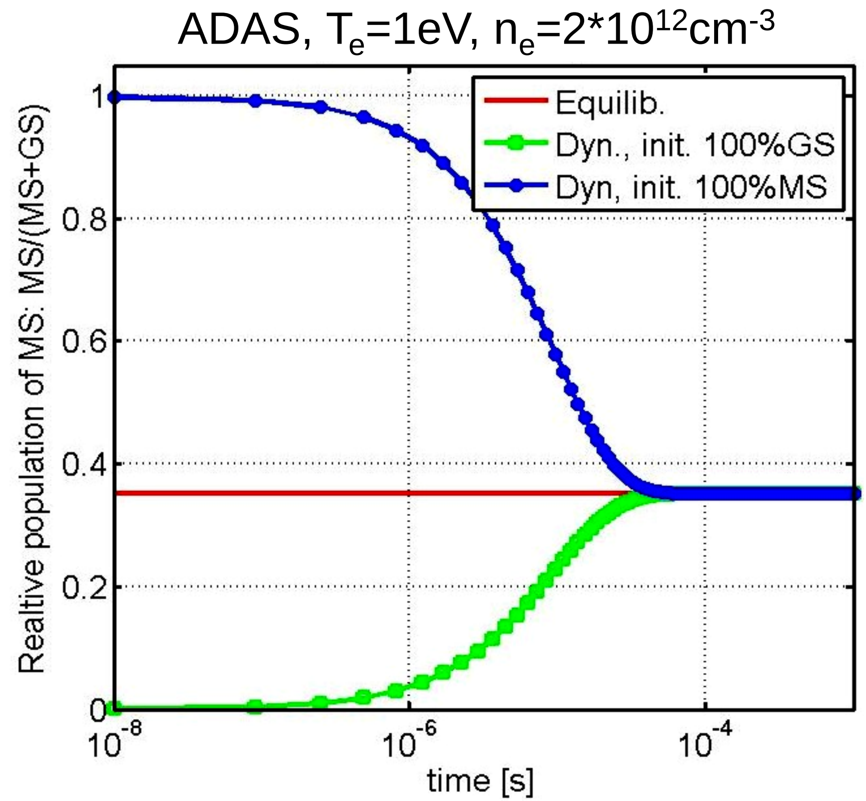
Additional sheath potentials: **V.Bobkov**

C.C. Klepper et al., J. Nucl. Mater. (2013), http://dx.doi.org/10.1016/j.jnucmat.2013.01.124

End



The system of 2 balance equations can be solved analytically . . .



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3,4) ionization from "GS" and "MS"

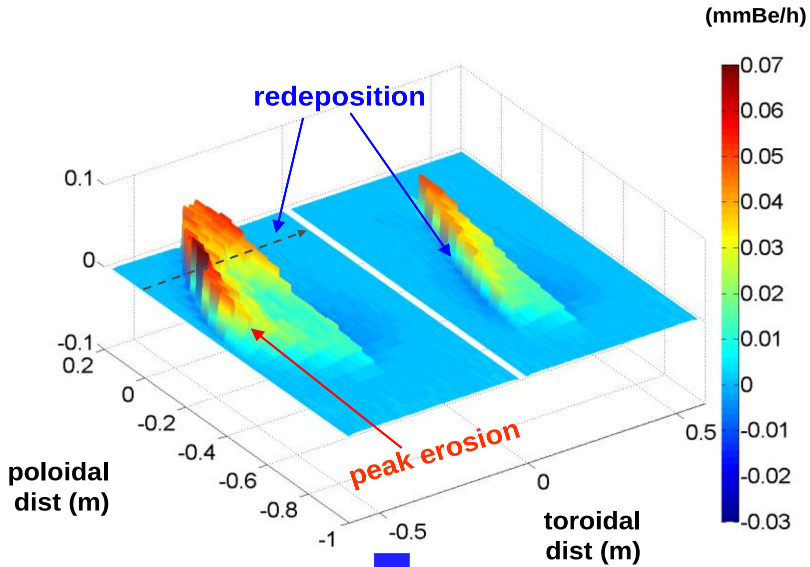
5,6) line intensity (PEC – photon emission coefficient), contributions from "GS" and "MS"

MS resolved approach allows to treat in ERO effectively the slow relaxation between triplet and singlet levels – important if MS population affected by extra processes and at high plasma parameter gradients

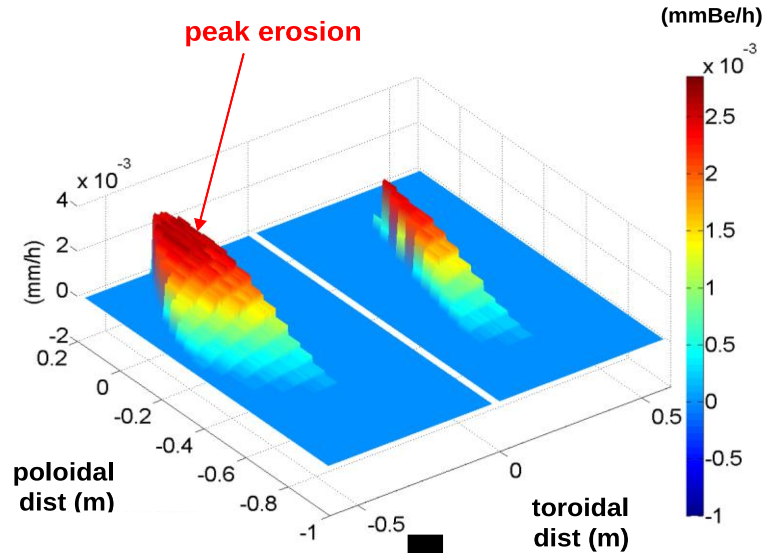
LIM code results

[S.Carpentier et.al, PSI-19, J.Nucl.Mater. (2010)]

2D Net erosion-redeposition patterns on BM11



High density case



Low density case

High density case

- ✓ $\langle Y_{eff} \rangle$ ~ 7%, ~50% particles locally redeposited
- ✓ Net peak erosion ~ 0.06 mm/h
  - ➔ PFC lifetime ~ 1500 shots
- ✓ T-retention* ~ 0.083 gT/h for one module
  - ~ 3 gT/h for 36 BM11-18
  - ➔ Limit ~ 1920 shots

(assuming: 50:50 D:T plasma, maximum safety limit ~640g)

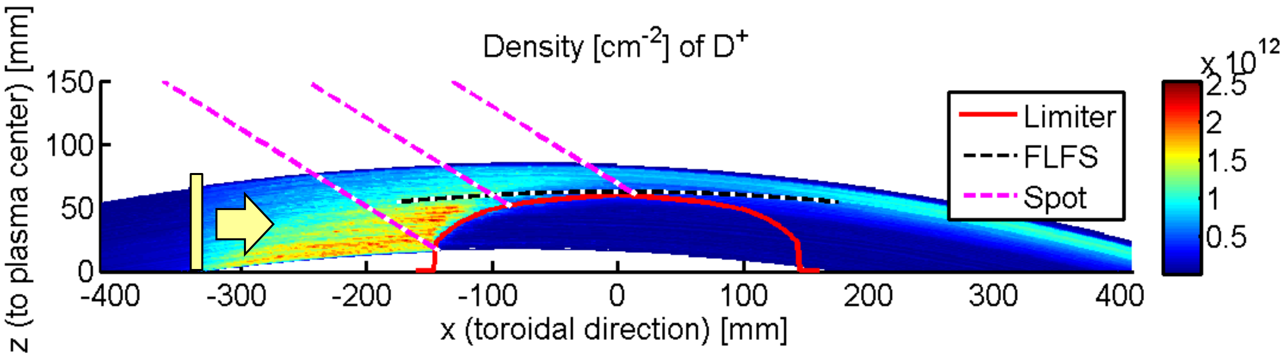
Low density case

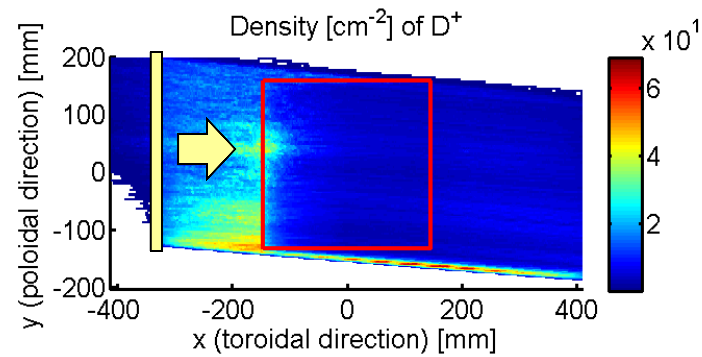
- ✓ $\langle Y_{eff} \rangle$ ~ 6%, ~10% particles locally redeposited
- ✓ Net peak erosion ~0.0025 mm/h
  - ➔ PFC lifetime ~ 36 000 shots
- ✓ T-retention* < 1.3 mgT/h for 36 BM11-18

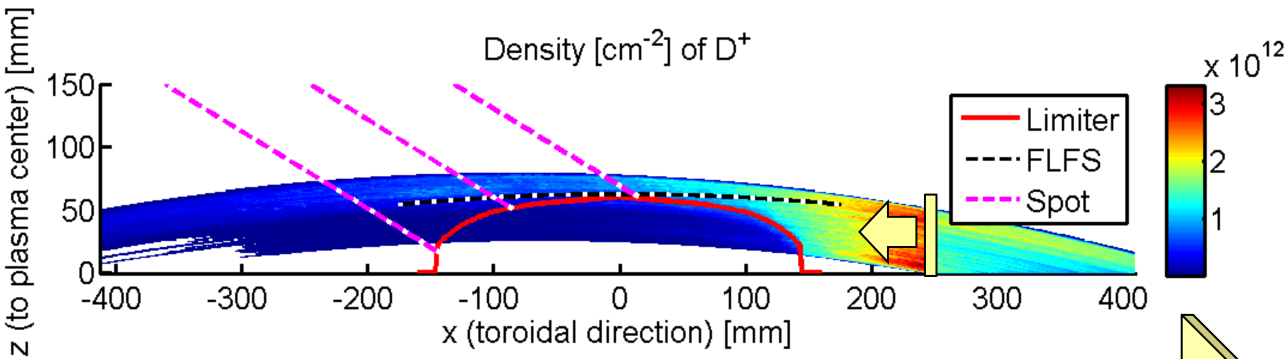
Important issue for ITER: benchmark with ERO focusing on life time

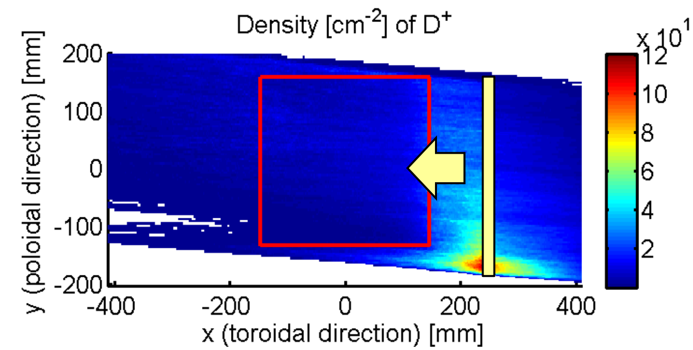
* 2D estimation of (D+T)/Be = f(T_{surf}, E_{imp}, Γ_D/Γ_{Be})
[PICSES-B scaling law, G. De Temmerman, R. Doerner]

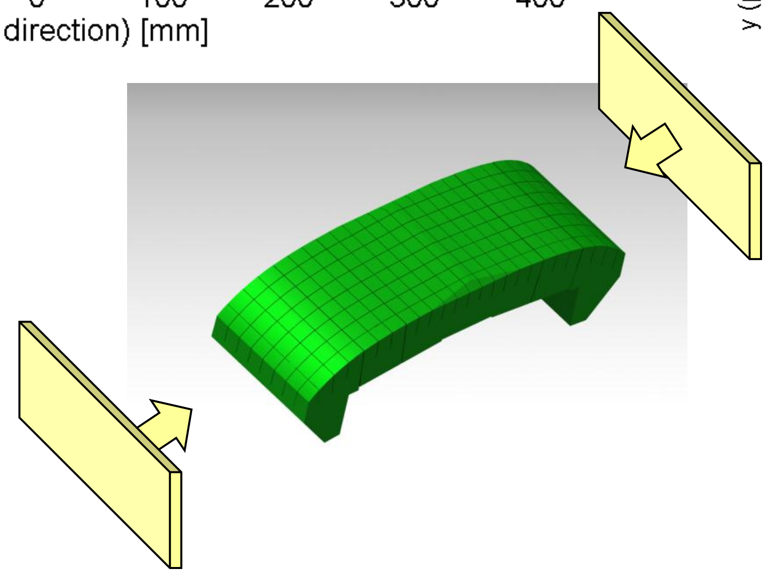
Gathering impact statistics . . .







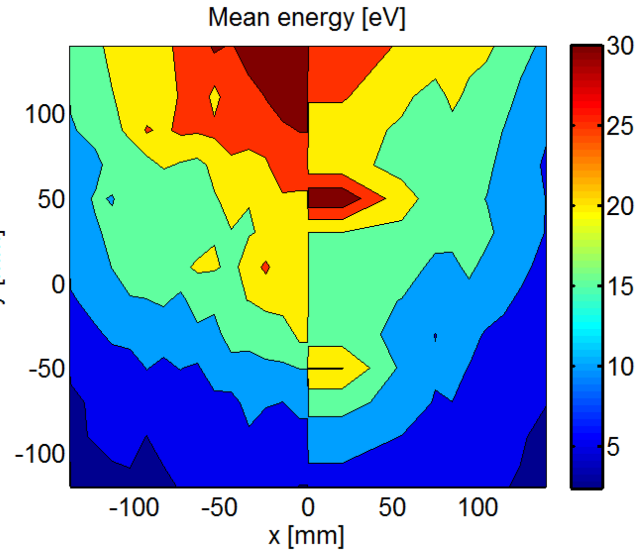


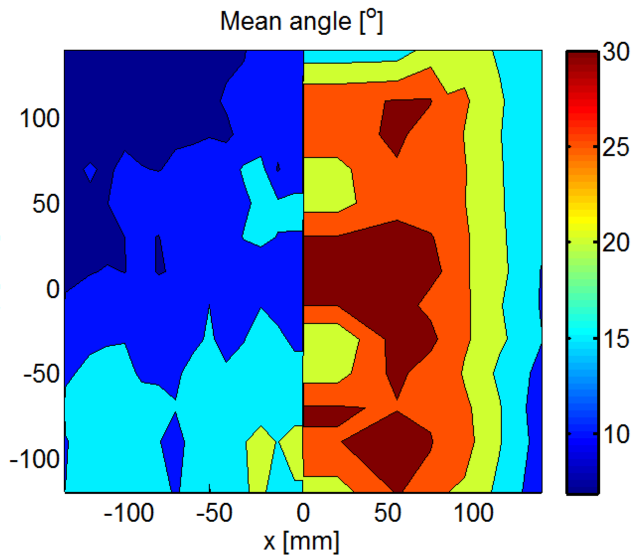


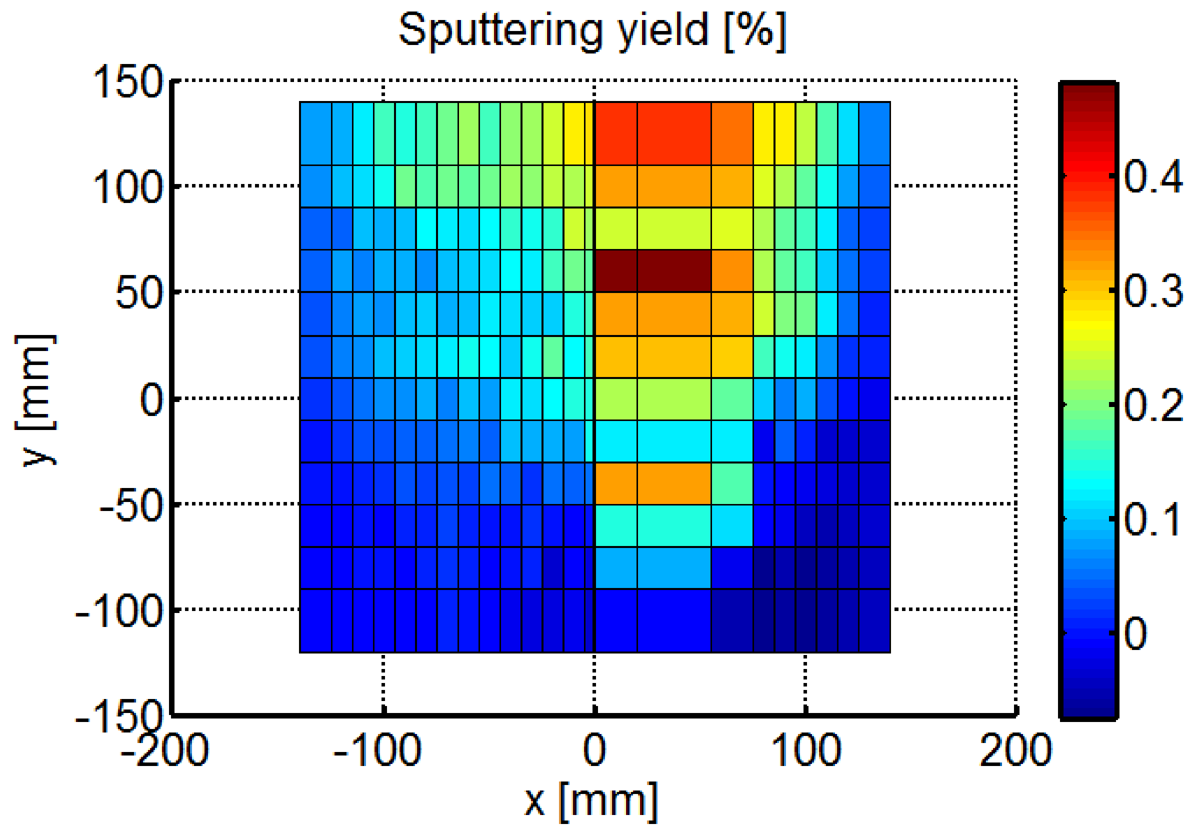
Averaged yield along the surface

Be by D⁺ sputtering

ERO "preliminary run"

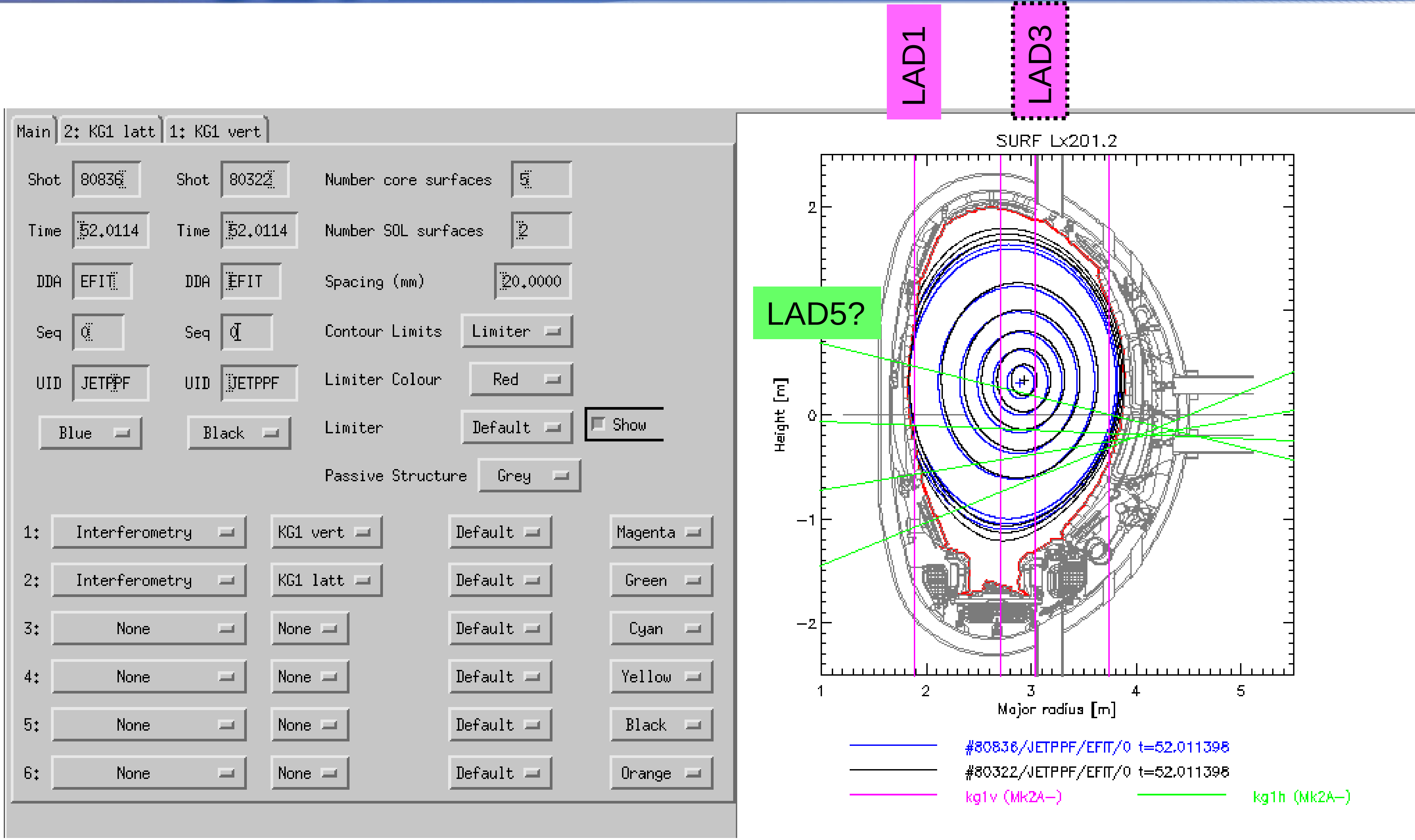






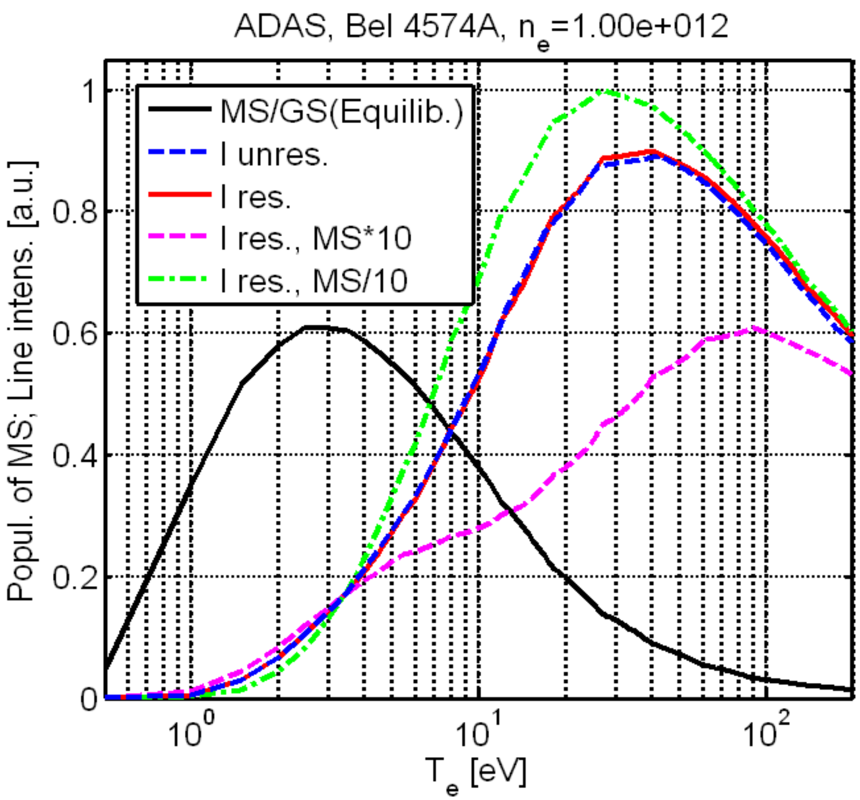
For testing purposeis it is easy to use in ERO „normal incidence + $E_{inc.}=E_{sheath}$ assumptions" . . .

ERO&Experiment: Bell light

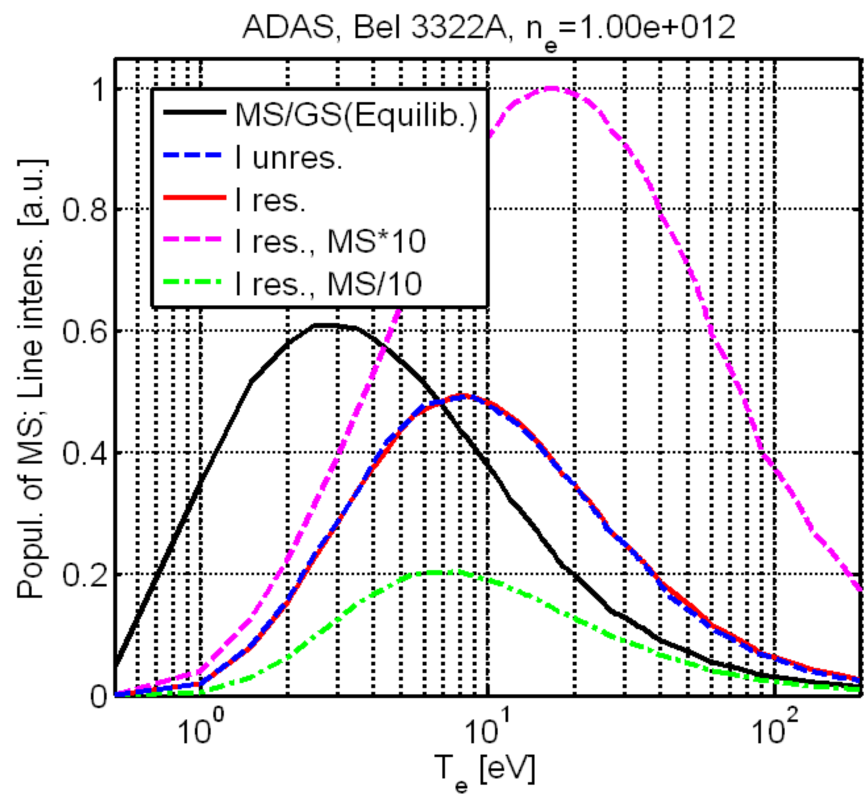


Line intensities – stationary approach

Singlet



Triplet



$$\begin{cases} \underbrace{0 \equiv}_{\substack{stationary\\ approach}} \dfrac{dN_{GS}}{dt} = -\langle ExGM \rangle N_{GS} - \langle IzG \rangle N_{GS} + \langle ExMG \rangle N_{MS} \\ dN_{GS} + N_{MS} = 1 \end{cases} \Rightarrow \quad \frac{N_{MS}}{N_{GS}} = \frac{\langle ExMG \rangle}{\langle ExGM \rangle + \langle IzG \rangle}$$

Be intrinsic impurity